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AUSTRALIA'S SUBMARINE DESIGN CAPABILITIES AND CAPACITIES

Challenges and Options for the Future Submarine

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Prepared for the Australian Department of Defence

RAND NATIONAL SECURITY RESEARCH DIVISION

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Preface

In the mid-2020s, the Royal Australian Navy (RAN) will retire the HMAS *Collins*, the oldest of Australia's *Collins*-class submarines, when it reaches the end of its nominal 30-year service life. Over the course of the following decade, the other five submarines that constitute the *Collins* class also could face retirement when their respective nominal service lives terminate.

The 3,000-tonne *Collins*-class vessels are amongst the largest conventionally powered submarines in the world. They have been the most survivable elements of Australia's military force since the *Collins* was commissioned in 1996. These diesel-electric attack submarines collect critical intelligence, maintain an Australian presence in maritime areas, and dissuade adversaries from interfering with Australia's maritime trade or from taking other hostile actions against Australia or its allies.

Australia intends to acquire 12 new submarines to replace the *Collins*-class vessels. As spelled out by the Australian Government in its *Defence White Paper 2009*,[1] this replacement submarine—known

[1] *Defending Australia in the Asia Pacific Century: Force 2030*, Defence White Paper, Department of Defence, 2009 (referred to as the *Defence White Paper 2009*).

as the Future Submarine—will be designed to travel farther, stay on patrol longer, support more missions, and provide more capabilities than the *Collins* vessels. At a minimum, the replacement will need to provide a range of warfare capabilities—anti-submarine; anti-surface; strike; intelligence, surveillance and reconnaissance; electronic warfare; mine warfare—and to support special forces and advanced force operations.[2]

The effort to acquire these new submarines will be the largest and most complex defence procurement in Australia's history, and the Australian Government is considering an option of designing domestically and building in South Australia. However, because Australia has not designed a submarine in the modern era, the Australian Department of Defence (AUS DoD) sought outside help to assess the domestic engineering and design skills that industry and the Government will need to design the vessels, the skills that they currently possess, and ways to fill any gaps between the two.[3] In November 2009, the AUS DoD engaged the RAND Corporation (RAND) to conduct such an evaluation of Australia's capabilities and capacities to design conventional submarines.

Between November 2009 and February 2010, a team of researchers from RAND, working closely with Australian and U.S. consultants—including a former CEO of the Australian Defence Science and Technology Organisation, a former director of the U.S. Navy Nuclear Propulsion Program's Resource Management division, a former director of the U.S. Naval Sea Systems Command's Submarine/Submersible

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2 *Defence Capability Plan*, Department of Defence, 2009, pp. 171–172; *Defence White Paper 2009*, pp. 70–71.

3 We capitalise the word Government when we are referring to the Australian federal Government. We use lower case when we refer to other government authorities, such as Australian state and territorial governments and foreign federal governments.

Design and System Engineering unit, a former technical director of the U.S. Navy's *Virginia*-class acquisition programme, a former director of naval architecture at Electric Boat Corporation, and a former commanding officer of a RAN submarine—conducted the evaluation. RAND's goal was to provide an independent, objective, and quantitative analysis that (1) describes the process of designing a modern, conventional powered submarine; (2) describes existing design resources in Australia that could support a future submarine design programme; (3) identifies and analyzes gaps between design resources that Australia currently possesses and those that would be required by a new submarine design programme; and (4) identifies and evaluates options whereby Australian industry could achieve the desired submarine design capabilities.

This study was sponsored by the Australian DoD's Defence Materiel Organisation, SEA 1000 Future Submarine Program Office.[4] RAND produced two versions of the final report: one which contains Commercial-In-Confidence information, and this one, which is suitable for general distribution. The research should be of particular interest to members of the RAN's submarine community; the Minister for Defence; the Minister for Defence Personnel, Materiel and Science; the Parliamentary Secretary for Defence Support; uniformed and civilian leaders in the military services; Members of Parliament; state and local authorities; and others in Government, academia, and the private sector interested in defence issues and in weapons-system development and acquisition.

This research was conducted within the Acquisition and Technology Policy Center of the RAND National Security Research Divi-

[4] The Future Submarine Program Office and other Government offices use *program* rather than *programme* in their official title. We follow this convention when referencing those offices, but in other usage we have striven to follow the conventional Australian spelling.

sion (NSRD). NSRD conducts research and analysis on defense and national security topics for the U.S. and allied defense, foreign policy, homeland security, and intelligence communities and foundations and other non-governmental organizations that support defense and national security analysis.

For more information on the RAND Acquisition and Technology Policy Center, see http://www.rand.org/nsrd/about/atp.html or contact the Director (contact information is provided on the web page).

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Summary

The Commonwealth of Australia will need a domestic workforce of roughly 1,000 skilled draftsmen and engineers in industry and Government to create and oversee the design of a new, conventionally powered submarine for the Royal Australian Navy. Although a workforce of this size and capabilities does not exist in Australia today, under the right circumstances one could be cultivated over the next 15 to 20 years. However, the Commonwealth could shorten the duration and lessen the costs of designing a new submarine if it were to collaborate with foreign design partners rather than rely exclusively on a domestic workforce to design the vessel.

So concludes our evaluation of Australia's capabilities and capacities to design conventionally powered submarines. In November 2009, the AUS DoD engaged RAND to independently evaluate and quantify issues connected with designing a new class of submarines that will replace Australia's six *Collins*-class submarines. The *Collins*-class vessels will begin to reach the end of their nominal 30-year service lives in the mid-2020s. At 3,000 tonnes, they are amongst the largest conventionally powered submarines in the world and have played a critical role for the RAN ever since the first vessel in the class, the HMAS *Collins*, was commissioned in 1996. As perhaps the most survivable elements of

Australia's military force, these diesel electric attack submarines collect intelligence, maintain an Australian presence in maritime areas, and dissuade adversaries from interfering with Australia's maritime trade or from taking other hostile actions against Australia or its allies.

Australia has committed itself to acquiring 12 new submarines to replace the *Collins* vessels, all of which face retirement by the mid- to late 2030s unless they undergo life extension programs. As detailed by the Australian Government in its *Defence White Paper 2009*,[5] this replacement submarine—known as the Future Submarine—will be designed to travel farther, stay on patrol longer, support more missions, and provide more capabilities than the *Collins* vessels.[6]

Acquiring these new submarines will be the largest and most complex defence procurement in Australia's history, and the Australian Government is considering an option of designing domestically and building in South Australia. However, because Australia has not designed a submarine in the modern era, the AUS DoD sought outside help to assess the domestic engineering and design skills that industry and Government will need to design the vessels, the skills that they currently possess, and ways to fill any gaps between the two. In November 2009, the AUS DoD engaged RAND to conduct such an evaluation of Australia's capabilities and capacities to design conventional submarines.

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5 *Defence White Paper 2009.*

6 At a minimum, the replacement will need to provide a range of warfare capabilities—anti-submarine; anti-surface; strike; intelligence, surveillance, and reconnaissance; electronic warfare; mine warfare—and to support special forces and advanced force operations. See *Defence White Paper 2009*, pp. 70–71, and *Defence Capability Plan*, Department of Defence, 2009, pp. 171–172.

RAND conducted this analysis between November 2009 and February 2010.[7] RAND's goal was to provide an independent, objective, and quantitative analysis that (1) describes the process of designing a modern, conventional powered submarine; (2) describes existing design resources in Australia that could support a future submarine design programme; (3) identifies and analyses gaps between design resources that Australia currently possesses and those that would be required by a new submarine design programme; and (4) identifies and evaluates options whereby Australian industry could achieve the desired submarine design capabilities.[8]

Overall Findings

Australia will need roughly 1,000 skilled draftsmen and engineers in industry and Government to create and oversee the design of a new, conventionally powered submarine for the RAN.

We found that Australian industry and Government possess a seedbed of personnel, software tools, and facilities that can grow to support the design of a new submarine. In Australian industry, numerous technical draftsmen and engineers exist who could contribute to

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7 In performing this study, RAND worked closely with Australian and U.S. consultants, including a former CEO of the Australian Defence Science and Technology Organisation, a former director of the U.S. Navy Nuclear Propulsion Program's Resource Management division, a former director of the U.S. Naval Sea Systems Command's Submarine/Submersible Design and System Engineering unit, a former technical director of the U.S. Navy's *Virginia*-class acquisition programme, a former director of naval architecture at Electric Boat Corporation, and a former commanding officer of a RAN submarine.

8 It should be noted that the design process we refer to here does not include the design of the combat system or of the propulsion system. At the direction of the Future Submarine Program Office, we did not address the designs of those systems in this research, since both are expected to be provided by vendors other than the submarine designer.

a new submarine design. Few of them have experience in submarine design, however, and their availability may be limited due to demands on their time from other commercial and naval programmes. This finding has three broad policy implications: First using this inexperienced domestic workforce instead of a fully experienced one to design the Future Submarine would lengthen the duration of time it would take to complete the design by three to four years and would increase the cost by about 20 percent. Second, adding submarine-experienced personnel from abroad would shorten the schedule and lessen the cost increase. And third, taking 20 years rather than 15 years to design the Future Submarine will reduce the peak demand for designers and draftsmen.

Focus of RAND's Research Effort

One strand of our research examined the processes that organisations use to design submarines. Another strand identified the resources—skilled personnel, software tools, and facilities—required by industry and Government to design a large, conventional submarine with the future capabilities outlined in the *Defence White Paper 2009*. This research strand also examined how different decisions about the conduct and content of the Future Submarine design programme can influence the magnitude and timing of demand for design resources. Based on several assumptions, we provided high and low estimates of personnel skill demand or requirements, plus a description of the facilities and software tools needed for a new submarine design.

Key Demand Caveat: Programme Decisions Have Yet to Be Made

Because the Future Submarine programme is in its infancy, nearly all key design decisions have yet to be made. Amongst the decisions facing

Australian defence decision-makers that will impact the design workload for both industry and Government are the following:

- setting the roles and responsibilities of industry and Government, which will impact the distribution of tasks
- setting the technical and operational requirements for the new submarine, which will impact the degree of technology advance needed
- selecting the specific design process (sequential, concurrent, or hybrid) to be employed
- specifying the level of detail in the design drawings that guide the production process, which can change the demand for draftsmen as well as the shape of the demand curve
- choosing to design or to buy major equipment and components[9]
- deciding when the first-of-class submarine will be required.

These uncertainties mean that it is quite challenging at this stage in the programme to make detailed projections of the total level of effort, the duration, or the design pace that the Future Submarine will require.

Demand for Industry Personnel

Our first step involved identifying skills that are required to design a submarine. All ship design programmes require the careful orchestra-

[9] Deciding to design or buy major equipment or components will be driven by other considerations. For example, selecting a foreign-designed combat system will limit the amount of other foreign participation in the programme. Intellectual property rights are another consideration. If Australia wants control over intellectual property, it will have to limit foreign involvement, which will affect the design effort. Decisions on either combat systems or intellectual property will drive how much technical transfer and assistance from abroad can be employed.

tion of a mix of skills and experience. The activities of draftsmen and engineers with basic marine engineering skills (such as naval architects, systems engineers, and marine engineers) and those skilled in specific systems (such as electrical and mechanical, or combat systems), as well as people experienced in project management, acquisition, contracting, and testing and commissioning—all must be choreographed.

Using a construct developed by the U.S. submarine designer General Dynamics Electric Boat Corporation,[10] we identified two broad skill competencies—draftsmen and engineers—made up of 17 discrete skill sets.

These skill sets became the foundation for how we estimated demand for industry design personnel brought about by the Future Submarine programme. To estimate the magnitude and timing of the demand for each skill, we employed a three-pronged analytical approach that entailed

- gathering and analysing historical design workload data on two conventional submarine programmes, the United Kingdom's (UK's) *Upholder* programme, which began in the 1960s and is now operated by Canada, and the *Collins* programme, which began in the 1980s and continues to the present[11]

[10] Two shipyards build U.S. nuclear submarines—General Dynamics Electric Boat in Groton, Connecticut, and Northrop Grumman Shipbuilding in Newport News, Virginia. Since January 2008, Northrop Grumman Shipbuilding has been the name of the submarine shipbuilding facility at Newport News, Virginia. It was known as Northrop Grumman Newport News from 2001 until 2008, as Newport News Shipbuilding from 1996 until 2001, and as Newport News and Dry Dock Company before then. For simplicity's sake, throughout this document we refer to the General Dynamics facility as Electric Boat (or EB) and to the Virginia shipbuilding facility as Newport News.

[11] The historical data on the *Collins* and the *Upholder* submarine design programmes were instructive. However, both programmes involved circumstances that are unlikely to be repeated in the Future Submarine effort (e.g., with the *Collins*, where the Commonwealth

- drawing on experienced submarine designers and programme managers to generate point estimates of workload levels and skill mixes that they expected would be required to design a large, conventional submarine with the future submarine capabilities outlined in the *Defence White Paper 2009*
- generating an independent set of estimates of the workload that will be required to design the Future Submarine, drawing from the RAND team's experience analysing submarine, maritime, and industrial design matters over many decades. We did so by constructing workload profiles for each skill that we had identified as being necessary for designing a submarine and summing those profiles over the roughly 15-year duration of the design effort.

This approach produced a range estimate of demand: The total workload to design a conventional submarine will require 8 to 12 million man-hours (MMH) of fully proficient, experienced industry design personnel.[12] This prediction is based on the Future Submarine's having

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assumed that the original Kockums 471 design would be more useful than it actually turned out to be). Moreover, our reconstruction of the data from those programmes might not have identified all of the man-hours required to design the respective vessels. Because the Future Submarine is likely to be larger, more technically complex, and have more stringent safety requirements, we took these data into consideration as only one element in the mix of data and expert opinions that we ultimately used.

[12] Decisions that could drive the total workload to the lower end of 8 million man-hours include less-challenging operational performance and capabilities and less-detailed drawings and other documents produced for construction. On the other hand, more-challenging operational performance and capabilities and more detail in the construction drawings could result in a total workload approaching the upper bound of 12 million man-hours. Different views exist as to whether concurrent design requires fewer design hours than the traditional design process during the design phase. However, most agree that savings will be captured during the production phase because fewer problems will be encountered during production. The man-hours shown here assume that major systems and components—power/energy, combat, etc.—will be bought and the only cost will be their integration into the submarine.

a design duration of 15 years and a design workload distribution that follows historical patterns. The peak demand at the total workload level would occur around year 7 of the design. At its peak, the workforce would number between 600 and 900 submarine-proficient technical personnel, comprising 300–450 draftsmen and 300–500 engineers.

Demand for Government Personnel

To oversee the submarine process, the Government is responsible for developing requirements and ensuring that the design efficiently meets those requirements. It does this by exercising technical authority, establishing safety criteria (supported by a thorough safety testing programme), engaging in programme management and oversight, and maintaining capabilities not supported by industry (such as specialised component design or research and development [R&D] programmes).

We also estimated the total number of engineering and project management personnel that the Government would need to oversee a submarine design effort. Based on historical U.S., *Upholder*, and *Collins* submarine design experience data, we estimated that the Government would require a workforce on the order of 15–20 percent of the total industry level of effort, a proportion depending largely on the level of involvement the Government chooses to have in the design. This translated into a dedicated Government effort of 80–175 personnel.

Demand for Facilities and Software Tools

The engineering facilities and software tools required for a submarine design depend on a variety of factors. These factors include the complexity of the submarine, the amount of design reuse from the previous generation of submarines, and the Government's acceptance of

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If major systems or components need to be designed and tested, those costs are in addition to those estimated here.

risk—both technical and operational. These choices, as yet unmade in the case of the Future Submarine, affect which facilities and tools are required.

Three categories of sophisticated modern design tools emerged in our analysis:

- Category 1: Tools that must be developed domestically and that, if absent, carry substantial risk to the design
- Category 2: Tools that need not be developed and that, if absent, carry moderate risk to the design
- Category 3: Tools that can be substituted with little or no attendant risk.

In all, we identified 20 distinct design areas that require facilities and software tools. And, although no one area is overly demanding, combining those 20 interrelated areas to design a vessel with a restricted internal volume that operates in a hostile operating environment is particularly difficult.

The engineering facilities required to support a submarine design can be grouped into three broad areas: combat systems; hull form design; and hull, mechanical, and electrical (HM&E) systems. For example, hull form design would require tow tanks, cavitation chambers, and acoustic measurement facilities. Facilities required to support submarine design can be located with industry, government, or academia. However, designers and engineers must have the level of access to the facilities required to support a submarine design.

Existing Design Resources in Australia That Could Support a Future Submarine Design Programme

To evaluate the current level of submarine-design resources in Australia, we sent detailed surveys to 46 industry firms, seven Government organisations, and three academic institutions. The survey posed various questions about the number and experience levels of skilled draftsmen and engineers, the ability to expand the workforce, and estimates of the future demand for the organisations' draftsmen and engineers. The survey also asked about facilities and software tools. We received responses from 28 industry firms, four Government organisations, and two academic institutions.[13] All the primary companies and organisations with submarine experience responded.

In many cases, companies did not, or could not, respond to all the survey questions. Follow-up interviews helped fill in our understanding of the data provided and some of the gaps, but we were forced to estimate some survey responses. This was a particular problem in the case of estimating future demand for personnel, both for personnel in general and for those with submarine-specific skills.

Our Estimate of Current Levels of Industry Personnel

Although thousands of draftsmen and engineers are employed in Australia, many work outside the defence sector, and few have relevant submarine-design experience. Table S.1 shows our estimate[14] of the

13 Follow-up interviews were conducted with many of the organisations that responded to the survey and with others that had not yet responded. We conducted interviews with additional Government organisations and with nine universities.

14 To make the estimate, we assumed that an existing combat system or a modification of an existing system would be used in the new submarine and that the majority of the combat-system design work would be accomplished by firms similar to those in our combat-systems group. Those firms have significant submarine experience and are typically offices of major

Table S.1
Summary Level Draftsmen and Engineers from Survey

	Total Number		Number with Submarine Experience	
Group	**Draftsmen**	**Engineers**	**Draftsmen**	**Engineers**
Platform design	374	1,215	196	262
Technical expertise	66	260		
Total[a]	462	1,548	206	275

[a] Includes a 5-percent factor for submarine-experienced personnel from the companies that did not respond to the survey

total number of draftsmen and engineers in the platform and technical groups that have submarine experience.[15]

international corporations that could provide resources for combat-system design. The main firm that designs the *Collins* class successor will require draftsmen and engineers who are experienced in integrating the combat systems with HM&E. We made a similar assumption for other major components of the new submarine. These components could be developed by the firms in our component group or procured from an international company. The design effort associated with these major components is not included in our demand estimates. However, we did include demands for the integration of these components into the HM&E of the new submarine.

[15] These draftsmen and engineers currently support other projects, and the precise future demand for the existing personnel is not clear from the survey responses. However, companies that employ submarine-experienced draftsmen and engineers stated in our follow-up interviews that their submarine workforces are engaged in through-life-support activities for the *Collins* class or are supporting the Air Warfare Destroyer programme. These companies' expectations of future revenue indicated that the future demand for these personnel is expected to stay steady or increase. There may be no idle submarine-experienced personnel to apply to a new submarine-design programme. As a result, submarine-experienced support personnel will need to be drawn from existing programmes to support the new submarine-design effort.

We estimated that 20–40 percent of the approximately 480 submarine-experienced draftsmen and engineers could be transferred from their existing programmes to help form the new design team. This would result in approximately 100–200 personnel who could serve as the base of the new submarine design team. Note that these people would be drawn from existing programmes and that they would therefore need to be replaced by new hires. Note also that some skills may be more difficult to build because there are so few personnel currently available to mentor new recruits. For example, there are minimal numbers of draftsmen with submarine heating, ventilation, and air conditioning system (HVAC) or piping skills and of engineers with communications, fluids, HVAC, propulsion, or testing skills.

Current Levels of Government Personnel: Our Survey and Estimate

We assessed the available Government submarine-design resources by surveying and/or interviewing a range of organisations involved in submarine design and sustainment and in other non-submarine maritime programmes.[16]

Table S.2 shows the number of Government engineers, scientists, and technical personnel that are presently dedicated to design or

[16] The submarine organisations included the Defence Materiel Organisation (DMO) Directorate of Submarine Engineering (DSME), the Defence Science and Technology Organisation (DSTO) Marine Platforms Division (MPD), the Maritime Operations Division (MOD), and the Submarine Combat System Program Office (SMCSPO). We sent a survey to but did not receive a response from the Collins Program Office (COLSPO), the Office of Director General Submarines, the DMO Maritime Systems Division (MSD), and the RAN Commander of Submarine Force. However, we subsequently learned that the COLSPO has been reorganized and now has three submarine-experienced personnel. This reorganisation is not reflected in Table S.2. With respect to non-submarine maritime programmes, we interviewed government representatives from the Air Warfare Destroyer (AWD) Alliance and gathered data about non-submarine maritime-engineering personnel within DMO and the Office of the Chief Naval Engineer (CNE).

Table S.2
Number of Government Engineers, Scientists, and Technical Personnel Presently Dedicated to Submarine or Other Maritime Design or Sustainment Activities

Organisation	Submarine Personnel	Other Maritime Personnel
DMO	87	391
DSTO	86	0
Navy	0	63
Total	173	454

sustainment or to other maritime programmes.[17] There are 173 full-time equivalent engineers, scientists, and technical staff members who are dedicated specifically to submarine design or sustainment in the organisations that responded to our survey. Another 454 engineers assigned to the DMO or the CNE on non-submarine maritime programmes may have expertise that is generally if not specifically relevant to submarine design work.

Broadly speaking, our surveys and interviews suggested that experienced submarine-design personnel are available. Across skill categories relevant to submarine design, the most significant capability resides in installation and testing of combat systems rather than in design, no doubt reflecting the ongoing Collins-class combat-system programme. In contrast, in the area of HM&E, the Government appears to have significant breadth but less depth.[18]

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[17] Table S.2 does not reflect DSTO personnel who are dedicated to non-submarine maritime science or technology; this information was not available at the time of writing.

[18] For example, there are few (if any) Government personnel specializing in propulsion, fluids, electrical systems, cost estimation, testing, and planning and production.

As described in the *Defence White Paper 2009*, several modernisation programmes compete for personnel required by the Future Submarine programme. On the one hand, these programmes may provide points of leverage to the extent that certain naval-engineering skills are transferrable between surface-ship and submarine programmes. On the other hand, these programmes may compete for the most-experienced technical personnel supporting Government work. In all cases, any assessment of capability gaps must account for these competing demands and reflect the fact that existing personnel are fully employed.

Our Estimate of Current Academic Capabilities

For reasons of scope, this study did not assess the capability or the capacity of the Australian educational system, broadly conceived. Rather, we focused more narrowly on a subset of universities and colleges that have programmes or departments in maritime- or defence-related science and engineering. In this regard, the Australian Maritime College (AMC) appears unique, offering both undergraduate and graduate-level courses in naval architecture, marine and offshore systems, and ocean engineering. AMC offers significant expertise and facilities that both industry and the Government could leverage in designing a future submarine.

Other generally relevant expertise may be more dispersed across universities and academic departments. The Future Submarine may be able to leverage these centres of expertise, but the challenge may lie in engaging and managing the distributed resources. The emerging Defence Systems Innovation Centre venture between the University of

Adelaide and the University of South Australia provides another model for such interaction between Government and academia.[19]

Our Survey of Existing Industry and Government Software Tools

Our surveys of, and interviews with, industry and Government organisations suggested that numerous software tools are utilised within the submarine and maritime communities today.[20] These tools range from computational programs for such areas as acoustics, structures, and hydrodynamics to complex, three-dimensional modelling software, many of which are available within Australian industry or in the United States.[21]

Our Survey and Estimates of Existing Design and Test Facilities in Industry, Government, and Academia

Industry, Government, and academia reported that they can access significant facilities either on-site or off-site. The Government facilities—located at DSTO, SMCSPO, and the Maritime Ranges System Program Office (MRSPO)—are heavily weighted towards combat systems and shock or acoustic testing. The majority of naval architecture facili-

[19] Discussions with AMC, the University of Adelaide, the University of Melbourne, the University of South Australia, Flinders University, Monash University, Deakin University, the Royal Melbourne Institute of Technology, Swinburne University, and the University of Melbourne suggest that Australia has strong educational institutions. AMC once again appears to be unique.

[20] Access to certain tools may be restricted if foreign design partners are involved in the programme.

[21] In general, Government organisations involved in *Collins*-class in-service support report using similar software tools in an effort to maximize efficiency. The DSTO and AMC report co-development of software tools used in complex hydrodynamic and naval-architecture research.

ties, including tow tanks and cavitation channels, are located at AMC but are primarily funded by DSTO.

It is important to point out that many of the facilities identified as available to industry are located at DSTO and AMC. When viewed as a pooled resource, Government and academia provide facilities for hull form development, hull form design, and combat system development and testing. Facilities located in industry tend to support the development of the hull, mechanical, and electrical design of the submarine.

Gaps Between Design Resources That Australia Currently Possesses and Design Resources That Would Be Required by a New Submarine Programme

Gaps exist in both industry and Government between the number of experienced design personnel who are available to work on a new submarine programme today and the number that a new submarine design programme would require. Fewer gaps exist with respect to the software tools and design/testing facilities that a new submarine will require.

Industry Personnel Gap

The number of experienced submarine design personnel employed by Australian industry today falls below the number that would be required to meet peak demands to design a new submarine. This shortfall is displayed in Table S.3, which shows the total number of skilled draftsmen and engineers available in Australia with submarine experi-

Table S.3
Submarine-Experienced Draftsmen and Engineers Available in Australia and Peak Demands, by Skill Category

	Skill Category	Number Available	Maximum Demand	
			8 MMH	12 MMH
Draftsmen	Electrical	12	64	96
	Mechanical	45	39	58
	Piping/HVAC	5	58	86
	Structural/arrangements	47	89	134
	Other	96	39	58
Engineers	Signature analysis	4	20	29
	Combat systems and ship control	7	51	77
	Electrical	16	39	58
	Fluids	1	26	39
	Mechanical	37	26	39
	Naval architecture	19	64	96
	Planning and production	2	13	20
	Structural/arrangements[a]	—	—	—
	Testing	1	7	10
	Management	1	13	20
	Engineering support	160	26	39
	Other engineering	22	39	58
Total		475[b]	613	917

[a]Grouped with naval architecture.
[b]Demands from other programmes may result in few (if any) personnel being available to support a new submarine design.

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ence and the peak demand estimated for those skills at the 8 MMH and 12 MMH demand levels.[22]

Government Personnel Gap

At first glance, our analysis of the supply of Government personnel resources suggests that the total number of personnel is sufficient to meet the estimated demand of 85 to 175 personnel. Across DMO and DSTO, our surveys indicated that there are more than 173 engineers currently associated with submarine design. The Government's existing submarine design workforce has a significant amount of experience from the *Collins*-class programme and has special capability in combat systems due to the design responsibilities assumed by SMCSPO. Moreover, there are about 450 engineers working within DMO and the CNE on non-submarine maritime programmes who may have expertise that is generally, if not specifically, relevant to submarine design.

However, this broad look ignores two important gaps. First, existing personnel are fully employed supporting the *Collins*-class or other RAN programmes and cannot contribute to a new submarine design without risk to ongoing RAN programmes. Second, our surveys indicated that there are too few personnel with skills anticipated to be important in the design of a future submarine. In particular, there are few if any resources in the discipline of large complex programme

[22] As noted above, the number of people with submarine experience in Australia does not imply these personnel are available to support the new submarine programme. Demands of other programmes will require the services of most, if not all, of these personnel. In all but the Other Engineering and Professional Support skill categories the number of individuals who are currently available is below the peak demand level. The Electrical and Piping drafting trades have less than one-third of the peak design requirement. Less than one-third of the peak design requirement is available in the Fluid Engineers, Naval Architects, Planning and Production, and Signature Engineers skill categories.

management and in specific areas related to propulsion, fluids, electrical systems, cost estimation, testing, and planning and production.

Tools and Facilities Gap

We found that Australian industry currently supports many software tools that would be required for a new submarine design programme and that the majority of the required facilities are available between Government, industry, and academia. The one critical gap that Australia will need to address entails a facility to test integrated propulsion and energy alternatives. While other facilities that do not currently exist in Australia can be "borrowed" from the United States or United Kingdom, we concluded that a new integrated propulsion/energy test facility should be built in Australia.

Options Whereby Australian Industry and Government Could Achieve the Desired Submarine Design Capabilities

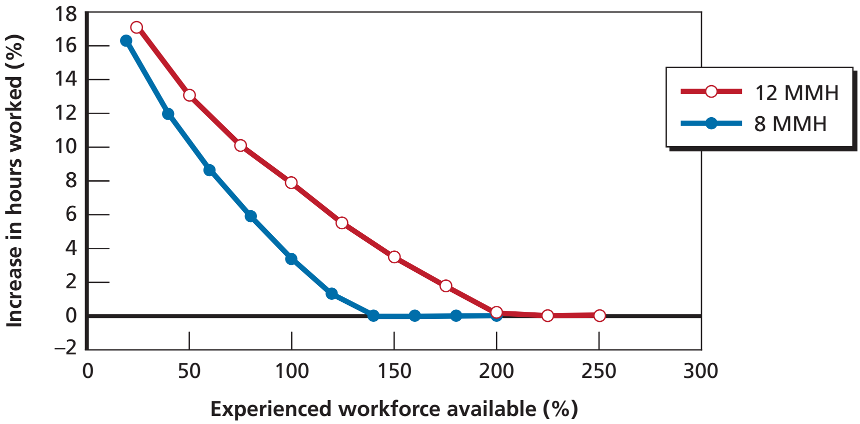
We evaluated two options that industry could pursue to cultivate submarine design expertise: (1) recruit new personnel solely from within Australia, and (2) infuse submarine-experienced personnel from other countries.

To evaluate these options, we constructed a simulation model to test how changes to the size and proficiency levels of the available design workforce would affect the man-hours and schedule required to design a new submarine.[23]

[23] The model starts with the annual demand for skilled personnel over the course of the design programme and a pool of submarine-experienced personnel to meet that demand. When the pool of experienced people is exhausted, a second pool of people with some distribution of general proficiency (but not submarine proficiency) is used to meet demand. These less-experienced personnel require training and mentoring, which result in less work

Sample outputs of the model are shown in Figures S.1 and S.2. Figure S.1 shows the relationship between total engineering man-hours and the percentage of Australia's current workforce submarine-experienced engineers who would be available to support the Future Submarine design programme.[24] Separate lines show the 8 MMH and 12 MMH design estimates. The figure shows that if 20 percent of today's 275-engineer workforce were available, total man-hours would increase by approximately 17 percent. If 150 percent of today's workforce were available (equal to some 400 engineers with submarine experience),

Figure S.1
Increased Engineering Hours Versus Skilled Workforce Available, 15-Year Design Profile



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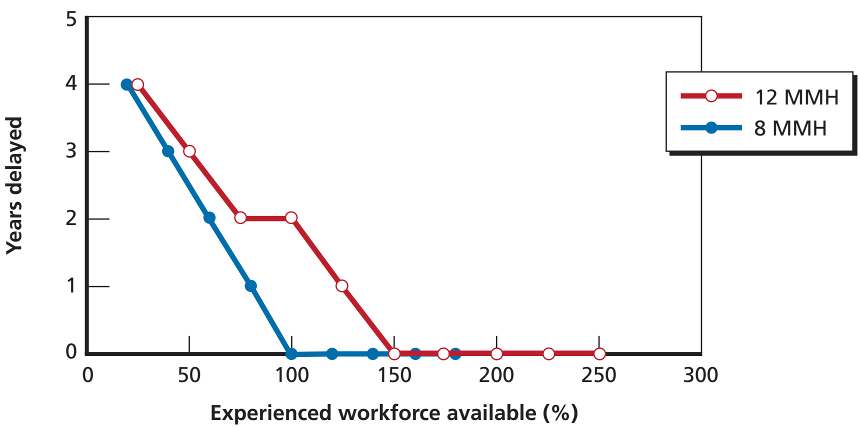
being performed than fully proficient workers can accomplish. Unaccomplished work in one period is pushed to the next time period.

[24] Separate analyses for draftsmen and total technical resources showed similar results.

total man-hours would not rise at the 8 MMH demand level. But to have the same effect at the 12 MMH demand level, approximately 550 submarine-experienced engineers would be necessary (or about twice as many as currently exist in Australia).

Figure S.2 shows the schedule impact as a function of the number of submarine-experienced engineers available to support the new submarine design programme. If 20 percent of the submarine-experienced engineers in Australia were available, the schedule would increase by approximately four years. That increase drops to three years if 40 percent of the skilled workforce were available. If all 275 submarine-experienced engineers were available, there would be no schedule delay for the 8 MMH demand; an additional 135 submarine-experienced engineers would be needed if the total demand is 12 MMHs.

Figure S.2
Schedule Delay Versus Skilled Engineering Workforce Available, 15-Year Design Profile



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The figures suggest two potential implications for recruiting:

- Building the design workforce solely with Australian resources could increase the total man-hours to accomplish the design by as much as 20 percent and delay its completion by three or four years. However, Australia would end up with a fully capable submarine design workforce that could work on both future submarine efforts and other naval programmes.
- Adding experienced submarine personnel from other countries could reduce or eliminate the additional man-hours and schedule delays. In addition, such a move would reduce the burden associated with drawing down the design team as the programme nears completion, because international workers could return to their home countries. However, collaboration may result in specialised skills or capabilities missing from the Australian workforce.

Evaluating Options for Closing the Gap in Government

At first glance, our analysis of the supply of Government personnel resources suggests that the total number of personnel is sufficient to meet the estimated demand of 85 to 175 personnel. However, this broad conclusion ignores the two important gaps in existing resources mentioned previously: (1) Existing personnel are fully employed on other RAN projects and (2) surveys indicate that there are too few personnel with experience in important skill categories. Although the Government appears to have ample expertise in areas related to combat systems, less experience in areas related to hull form and HM&E design may introduce risks to the Future Submarine programme.

To close the Government personnel gap, we recommend drawing a core of technical personnel from the support of the *Collins* class and other maritime programmes and hiring additional personnel both as replacements for core personnel and to fill out the Future Submarine programme. This would leverage the *Collins*-class experience, reduce the risk of under-resourcing the support to the *Collins* class and other programmes, and keep training costs reasonable.

Evaluating Options for Closing Tools and Facilities Gap

To close the skill and technology gap, we recommend leveraging existing relationships with allied nations to "reach back" for capability in the areas of combat systems and hull form design. Access to propulsion and energy system technology from allied partners may be limited. Therefore, long-term investments in land-based test facilities and expertise will be required to close the HM&E gap.

Policy Considerations

We found that a core of technical resources, including personnel, software tools, and facilities, exists in Australian industry and Government that can evolve to support the design of a new submarine. There are numerous technical draftsmen and engineers in Australian industry who could contribute to a new submarine design. However, few of those technical personnel have experience in submarine design. Furthermore, the demands of other commercial and naval programmes, including the support for the *Collins* class, may limit the availability of the technical workforce, especially people skilled in submarine or naval systems.

These findings lead to several policy considerations:

- Forming the design team for the new submarine from in-country resources could increase the total man-hours to accomplish the design by approximately 20 percent and cause the schedule to lengthen by three to four years. Nevertheless, this is an investment in developing technical and managerial expertise that the Commonwealth's senior leaders may choose to make.

- Adding submarine-experienced personnel from other countries could result in a smaller increase in man-hours and a shorter schedule. These personnel could be recruited by the platform design firm, come from international offices of Australian companies, or result from collaboration with an international submarine design and construction company.
- Lengthening the time to design the Future Submarine from 15 to 20 years while not changing the required fully proficient man-hours could reduce the peak requirements for skilled personnel and, as a result, could reduce the total man-hours needed to accomplish the design and could allow needed technologies to mature.
- Although extending the design period could reduce the increase in man-hours from an inexperienced workforce, designing the Future Submarine in flights would not necessarily have the same impact.[25] The design of the first flight would be basically a "new" submarine; subsequent flights would have smaller peak demands and could help in sustaining future submarine design capability.
- Programme management skills are important in both industry and Government. Those possessing such skills are the leaders who must guide the Future Submarine programme to a successful conclusion.
- Building up an in-country design capability and then letting that capability wane after the completion of the design effort might be counter-productive. Technology advances by regional countries or

[25] The concept of flights applies to subsequent submarines of a class and has *no* effect on the numbers of people required to design the first of the class or the duration of the design.

a change in mission priorities will require the Australian defence forces to sustain a capability advantage in the region. This capability edge requires a sustained submarine technical capability. Continued employment of the first-of-class design workforce to build updated models or flights of the initial submarine would help maintain the design workforce over a longer period of time. Also, technical personnel in both industry and Government are needed to conduct and oversee the initial production programme and could also provide in-service support to the new submarine.

Acknowledgments

This research could not have been accomplished without the assistance of people from across industry, Government, and universities in the Commonwealth of Australia. The complete list of names and contributors would fill several pages. Nevertheless, we need to call out particular assistance we receive from several individuals who supported this work in extraordinary ways. In the SEA 1000 Future Submarine Program Office, RADM Rowan Moffitt, Royal Australian Navy, Head SEA 1000; David Simcoe, Engineering Manager; and Mark Gairey, Project Director, continually encouraged and supported this research effort.

In industry, individuals from numerous Australian firms shared their knowledge of the submarine design process and their firms' industrial capabilities and provided data necessary to accomplish our analysis. Their response to our questions and formal survey helped us understand the challenges Australia faces in designing the Future Submarine. We are particularly indebted to Graeme Bulmer, Jack Atkinson, and Rolf Polak of the Australian Submarine Corporation, who arranged for our numerous visits to their facilities and our meetings with individuals directly involved with designing, managing, and maintaining the Commonwealth's *Collins*-class submarine programme.

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Last, the authors owe RAND colleague Joan Myers an incalculable debt for her thoughtful and patient administrative assistance at every step. The authors, however, are solely responsible for the interpretation of the information and data and the judgements and conclusions drawn. And, of course, we alone are responsible for any errors or omissions.

Abbreviations

3D	three dimensional
AIP	air-independent propulsion
AMC	Australian Maritime College
AMCE	Aerospace & Mechanical Consulting Engineers
AMT	Australian Marine Technologies
APS	Applied Physical Sciences
ASC	Australian Submarine Corporation
ATPC	Acquisition and Technology Policy Center
AUS DoD	Australian Department of Defence
AWD	Air Warfare Destroyer
C4I	command, control, communications, computers, and intelligence
C4ISR	command, control, communications, computers, intelligence, surveillance, and reconnaissance
CAD	computer aided design
CAE	computer aided engineering

CFD	computational fluid dynamics
CFE	contractor-furnished equipment
CFM	contractor-furnished material
CNE	Chief Naval Engineer
COLSPO	Collins Program Office
COTS	commercial off-the-shelf
CPM	critical path method
DDAM	dynamic design analysis method
DMO	Defence Materiel Organisation
DSIC	Defence Systems Innovation Centre
DSME	Director, Submarine Engineering
DSTO	Defense Science and Technology Organisation
EB	General Dynamics Electric Boat Corporation
EMC	electromagnetic compatibility
EMF	electromagnetic field
EMI	electromagnetic interference
EPCM	engineering, procurement, construction management
ESP	external service provider
FSM	Future Submarine
FTE	full-time equivalent
GFE	government-furnished equipment
GFI	government furnished information
GMEC	Governmental Marine Excellence Centre

HM&E	hull, mechanical and electrical
HMAS	Her/His Majesty's Australian Ship
HSI	human system integration
HVAC	heating, ventilation, and air conditioning system
IDES	Integrated Design & Engineering Solutions
IMS	integrated master schedule
IPDE	Integrated Product Data Environment
IPMS	Integrated Platform Management System
IPPD	Integrated Product and Process Development
IPT	integrated project team
IR	infrared
IS	information security
L3	L3 Nautronix
LBES	land-based experiment systems
LHD	landing helicopter dock ship, amphibious assault ship
LM	Lockheed Martin
LSV	large-scale vehicle
MAIT	major area integration team
MAP	manufacturing and assembly plan
MAT	major area teams
MMH	million man-hours
MoD	Ministry of Defence
MOD	Maritime Operations Division

MOTS	military off-the-shelf
MPD	Marine Platforms Division
MRSPO	Maritime Ranges System Program Office
MSD	Maritime Systems Division
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis programme
NSRD	National Security Research Division
NTS	National Technical Systems
PA	product area
PEM	proton exchange membrane
PERT	programme evaluation and review techniques
PIT	process integration teams
PMB	Pacific Marine Battery
PMT	project management team
PSG	programme steering group
R&D	research and development
RAN	Royal Australian Navy
RAND	RAND Corporation
RANRAU	Royal Australian Navy Range and Assessment Unit
RCS	radar cross section
RFI	request for information
ROM	rough order of magnitude
SATCOM	satellite communications

SEA 1000	Australian Future Submarine Program
SIT	system integration team
SKM	Sinclair Knight Merz
SMCSPO	Submarine Combat Systems Program Office
SS	submarine fast attack
SSN	nuclear attack submarine
SVT	SVT Engineering Consultants Pty Ltd
UGL	United Group Limited
UK	United Kingdom
U.S.	United States
VBROP	Visual Basic Ram/Radome Optimisation Program

CHAPTER ONE

Introduction

Australia's *Collins*-class submarines will begin to face retirement from service in the mid-2020s, if they do not undergo a life extension programme. In the recent *Defence White Paper 2009*,[1] the Australian Government declared that 12 new conventionally powered future submarines would replace the *Collins* class. This replacement submarine—known as the Future Submarine—will be designed to travel farther, stay on patrol longer, support more missions, and provide more capabilities than the *Collins* vessels. At a minimum, the replacement will need to provide a range of warfare capabilities—anti-submarine; anti-surface; strike; intelligence, surveillance and reconnaissance; electronic warfare; mine warfare—and to support special forces and joint/coalition force operations.[2]

The *Defence White Paper 2009* also recognises the importance of the Australian defence industry in supporting the design, development, construction, and in-service support of Australia's current and future

1 *Defending Australia in the Asia Pacific Century: Force 2030*, Defence White Paper, Department of Defence, 2009 (referred to as the *Defence White Paper 2009*).

2 *Defence Capability Plan*, Department of Defence, 2009, pp. 171–172; *Defence White Paper 2009*, pp. 70–71.

defence force.[3] Although recognizing that total self-sufficiency in all defence industry capabilities may be impractical and unwarranted, the Government intends to support a set of key domestic strategic industrial capabilities. To evaluate the extent of Australian industry support and roles in the Future Submarine programme, the Government needs to understand the feasibility and the options for designing the new submarine using Australian industry and Government resources, perhaps augmented by foreign partners.

The design of a submarine is a complex task requiring a range of resources, including skilled personnel, a suite of software design tools and databases,[4] and various test and trial facilities. Undertaking a new design for the Future Submarine programme could prove to be especially challenging because it will be the first submarine designed primarily by Australian industry. While similar challenges were faced and addressed during the build of the *Collins* class, it is important for the Future Submarine programme to understand the costs, benefits, and risks of various options for delivering the desired design products.

Research Objective

To understand better the feasibility of undertaking the design of the new submarine, the Australian Government asked RAND's National Security Research Division to address four questions:

1. What is involved in designing a new submarine and what is the demand for various design resources during the conduct of the design programme?

[3] *Defence White Paper 2009*, Chapter 16.

[4] The entire suite of software required to design, build, and support a product is sometimes referred to as its Integrated Product Data Environment (IPDE).

2. What design resources currently exist in Australia?
3. What is the "gap" between what is needed and what is available?
4. What is the cost and effectiveness of options for closing the gap?

This monograph focuses on the answers to these questions.

Research Approach and Considerations

The resources required for a new submarine design programme involve personnel with various skills and proficiencies, facilities for testing and evaluating design concepts, and computer software for developing designs and producing detailed drawings needed for construction. These three types of resources—people, facilities, and software—are needed not just by the contractor responsible for design integration but also by the Government and critical vendors that design submarine components.

This research draws upon a large body of prior research conducted by RAND in submarine and naval ship design in the United States and United Kingdom (UK).[5] To estimate the resources required for a submarine design, we supplemented the knowledge drawn from the prior research with historical data on the *Upholder* (UK) and *Collins* (Australia) design programmes and the judgements of several subject matter experts in submarine design. Although we based our estimates of the skills that Australia would require mainly on our U.S. and UK experience, we allowed for key differences in process and technology (e.g., nuclear versus conventional propulsion, owning rather than

[5] For example, see John F. Schank, Mark V. Arena, Paul DeLuca, Jessie Riposo, Kimberly Curry, Todd Weeks, and James Chiesa, *Sustaining U.S. Submarine Design Capabilities*, Santa Monica, Calif.: RAND Corporation, MG-608-NAVY, 2007.

buying design facility/tool services). Similarly, we based our estimates of demand for facilities and infrastructure to support design on our knowledge of the U.S. and UK approaches, modified for factors unique to Australia.

Unfortunately, there is no specific level of demand for skills at various Government and industrial base organisations over the course of a new submarine design programme. Many factors influence the number and types of design resources, where they are located, and when they are needed.[6] Such factors include

- roles and responsibilities of Government and industry
- the amount of programme risk to be accepted, mitigated, or avoided
- technical decisions on desired performance parameters (e.g., propulsion, weapons systems, quieting)
- the type of design effort required (evolutionary versus revolutionary)
- the design process to be employed (a sequential process, a concurrent design/build process, or a hybrid design development approach)
- the level of detail required in drawings and exact nature of required design deliverables (e.g., product model data, work packages, drawings)
- the level of experience of the workforce and management

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[6] Deciding to design or buy major equipment or components will be driven by other considerations. For example, selecting a foreign-designed combat system will limit the amount of other foreign participation in the programme. Intellectual property rights are another consideration. If Australia wants control over intellectual property, it will have to limit foreign involvement, which will affect the design effort. Decisions on either combat systems or intellectual property will drive how much technical transfer and assistance from abroad can be employed.

- decisions on making versus buying major components, systems, and services.

Because numerous factors must be addressed when answering the question of what resources are required to design a new submarine, we provide a range of possible resource requirements and weigh how various decisions can impact the number, type, and location of design resources.

To assess the submarine-design capabilities within Australia, RAND developed a survey instrument. The survey was sent to organisations within government, industry, and academia to collect information about each organisation's submarine-design capabilities, including provision of submarine products and services, submarine-related skills, design tools and processes, and submarine facilities.

We specifically focused on answering the following questions:

- What is the current number of technical personnel employed in industry, academia, and throughout the Australian Department of Defence who could contribute to the Future Submarine design effort?
- What is the submarine-related experience of those personnel?
- What will the future demand for their technical resources be?
- What are the organisations' perspectives on expanding their technical workforce to meet future demand, including, potentially, demands arising from the Future Submarine programme?
- What design tools and facilities appropriate for a new submarine-design programme are available in Australia?

Comparing the demand for design resources with the supply available in Australia provides an estimate of the gaps facing Australian industry and the Government. Currently, there is a substantial difference between the personnel resources in Australian industry that could be available to support a new submarine design and what is actually needed to support that design. There are also some shortfalls in software tools, facilities, and Government personnel, but the most significant challenge faced by the Future Submarine programme in conducting a domestic design effort is building up the design workforce and organisation at whatever entity is selected to carry out Future Submarine design.

To estimate the impact of the gaps on the duration of the design and the total number of man-hours required, we constructed a model that simulates the growth and proficiency level of the design workforce. Inputs to the model included (1) the annual number of fully proficient man-hours required to complete the design over the duration of the design programme and (2) the size of the submarine-experienced workforce available at the start of the design process. Other inputs include the availability of personnel at different proficiency levels, mentoring ratios, and the maximum rate at which the design workforce can expand annually. Model outputs included a profile of the workforce buildup (and drawdown), the time required to complete the design, and the total number of man-hours needed to reach the required number of fully proficient man-hours.

The options for closing the gap basically relate to the number of submarine-proficient draftsmen and engineers available to augment existing assets. Recruiting new personnel in Australia could lead to the employment of a greater number of new personnel who are not proficient in submarine design and would therefore require additional time and man-hours to complete the tasks. Infusing personnel experienced in submarine design by either recruiting draftsmen and engineers from outside Australia[7] or collaborating with an experienced submarine-design company may result in closer alignments with the schedule and with the required number of fully proficient man-hours. In addition to their effects on time and man-hours, these options have other advantages and disadvantages, especially when planning for meeting future demands on the submarine-design capability.

Organisation of the Monograph

Following this introduction, we first describe our analysis of the demand for submarine design resources. Chapter Two describes and defines the skills and processes required to design a modern conventional submarine. Chapter Three goes on to detail estimates made by RAND and outside experts of the level and pace of demand for personnel that will be required to design the Future Submarine. Chapter Four explores the expected demands that the Future Submarine programme will place upon Government technical and management expertise. Chapter Five discusses demand for non-personnel design resources that might arise over the course of the Future Submarine programme, including design software and various types of test, trial, and acceptance facilities.

We then turn to the question of the level of submarine-design resources in Australia. Chapter Six describes the survey used to collect data and how the firms that responded to the survey were grouped for analysis. Chapter Seven estimates the submarine-design resources that currently exist in Australia, and Chapter Eight estimates Govern-

[7] For example, the Australian offices of companies such as BAE, Babcock, and BMT could "reach back" to corporate offices in other countries to augment their Australian-based draftsmen and engineers, to the extent that can be accomplished without incurring intellectual property or technology transfer issues or adversely affecting home-country programmes.

ment resources. Chapter Nine describes resources in academia and the role Australian universities can play in the Future Submarine design programme.

The final part of the monograph describes the gaps in industry and Government between what is needed and what exists within Australia and evaluates options for closing those gaps. Chapter Ten compares the supply and the demand to define the gaps that exist and presents various options for closing the gaps. Chapters Eleven through Thirteen provide the evaluation of those options. Finally, Chapter Fourteen provides the findings of the analysis and concluding comments.

The monograph also contains five appendices, one on operational safety considerations, another on the design process known as the integrated product and process development process, a third that displays industry workload profiles by skills, and a fourth that expands upon the discussion of design tools in Chapter Five. A fifth and final appendix presents the survey instrument used to collect data from Australian organisations. A bibliography completes the monograph.

CHAPTER TWO

Submarine Design Skills and Processes

This chapter provides a general description of the skills and processes necessary to design a modern conventional submarine. We outline the competencies that must reside in industry and Government and the multiple design processes that the Commonwealth could employ to capitalise on these skills.

Any ship design programme requires careful orchestration of a mix of skills and experience to complete the design process. These include draftsmen and engineers with basic marine engineering skills (such as naval architects, systems engineers, and marine engineers) plus those skilled in specific systems (such as electrical and mechanical, or combat systems). People experienced in project management, acquisition, contracting, testing, and commissioning are also required.

In addition to general ship design and engineering resources, submarine design requires additional unique competencies—such as shock survivability, atmosphere control, and SUBSAFE-type quality issues—many of which do not directly overlap with surface ships.[1] Submarines

[1] SUBSAFE is a quality assurance programme intended to maintain the submarine fleet's safety by maximizing assurance that submarine hulls will remain watertight and be able to recover from unanticipated flooding. It encompasses all systems exposed to sea pressure or critical to flooding recovery.

also have unique stealth features requiring specialised noise and vibration skills and propulsion plants requiring other unique skill sets.

Personnel with these competencies are employed at various times throughout the design process and can reside within various organisations. Each organisation has a specific role to play in the design process and brings a unique set of design skills to the process. However, as we note in Chapters Three through Five, the total level of effort and precise mix of skilled personnel that will be required to design the lead Future Submarine depend on a number of decisions that have not yet been made.

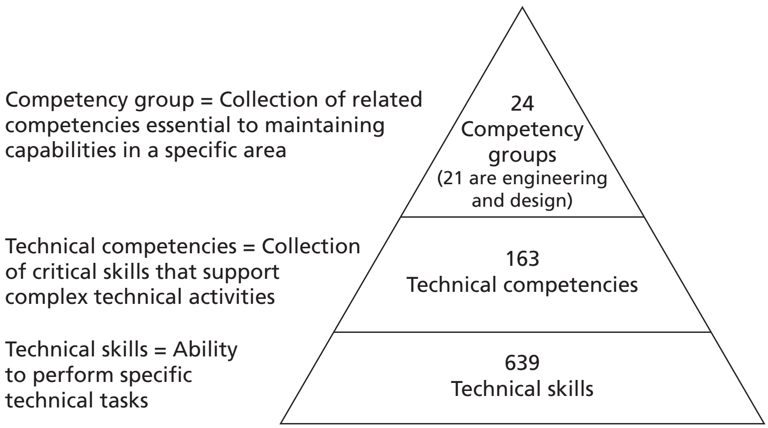
Beyond human capital, submarine design also requires tools and facilities to support the design work, which we discuss in more detail in Chapter Six.

Industry Skills Required to Design Submarines

In 2004, the General Dynamics Electric Boat Corporation (EB), a U.S. submarine design and construction firm, undertook an effort to categorise the skills required for a submarine design effort. It defined each design task, and then identified the necessary skills to perform the task. It identified 639 technical skills required in the nuclear submarine design process, shown as the base of the pyramid in Figure 2.1.

Once it had identified all of the skills, EB organised them into groups based on similarities. These groups were referred to as technical competencies, shown as the middle section of the pyramid. EB identified 163 technical competencies. Finally, EB used similarities between the technical competencies to develop 24 competency groups, shown as the top of the pyramid.

Figure 2.1
Electric Boat Categorisation of Submarine Design Skills



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While instructive, this EB breakdown of skills and competencies proved to be analytically unwieldy for the purposes of this analysis. As a result, for this project, we combined the 24 major competency groups identified by EB into a list of 17 competencies that we believe reflect a more analytically manageable set of skills that platform contractors require to design conventional submarines (see Table 2.1).

Further, we divided those 17 competencies into two primary groups—draftsmen and engineers. Draftsmen create technical drawings or operate tools that create the technical drawings used in production. They typically receive training at trade schools and on the job. Engineers, on the other hand, provide engineering analysis and technical assessments. They perform calculations to establish and verify that the drawings produced, if built, will produce the desired technical specification. Managers and administrators support both of these technical groups.

Table 2.1
Industry Competencies Required to Design Submarines

Skill Competencies		Example Activities/Products
Draftsmen	Electrical	Electrical system component, electrical analysis, electrical design, power generation
	Mechanical	Mechanical component, mechanical system, mechanical design,
	Piping/HVAC	Piping design, heating, ventilation, and air conditioning design, fluid system design, hydraulic system design
	Structural/ arrangements	Structural engineering, structural arrangement, structural design
Engineers	Signature analysis	Acoustic, wake, thermal, electromagnetic, and other signature analysis
	Combat systems and ship control	Combat system integration, combat system design, ship control and navigation
	Electrical	Electrical motor and generator design, distribution, control, load analysis, component design and safety
	Fluids	Hydraulics, chilled and cooling water, flow analysis, computational fluid dynamics (CFD), flooding and casualty analysis
	Mechanical	Mechanical components, mechanical systems, mechanical design, weapons-handing systems, rotating machinery, auxiliary machinery
	Naval architecture	Hydrostatics, hull equilibrium, speed and powering analysis, stability
	Planning and production	Scheduling, manufacturing planning, production strategy development, producibility analysis, production support, zone and block outfitting planning, procurement

Table 2.1—Continued

Skill Competencies		Example Activities/Products
	Structural/ arrangements	Hull design, casing design, deck layouts and design, equipment arrangements, shock analysis, foundation designs
	Testing	Component and system testing, test and trials plan development
	Management	Programme management, technical management; supervision
	Engineering support	Non-engineering support, such as technical, computer, and information technology specialists
	Other engineering	Life cycle support, cost, availability analysis, risk management, safety, environmental, materials

This list of competencies serves as a base for competencies required to design a conventional submarine. However, the number of primary competencies could increase if the platform contractor performs functions that have typically been performed by military off-the-shelf or commercial off-the-shelf (MOTS/COTS) vendors in the United States and UK. If, for example, appropriate MOTS/COTS systems for (say) propulsion design and engineering, and/or communications and sensors capabilities are unavailable, design skills in these areas may be required by the platform contractor to execute the overall design of the submarine. In addition, the decision to utilise emergent technologies could require additional competencies (e.g., the use of increased automation or of advanced materials, composites, or air-independent propulsion [AIP] technologies, would all require such competencies to be added to Table 2.1).

Government Skills Required to Manage Submarine Design Efforts

The capabilities that the Government must have will depend upon the desired role of the Government in the submarine design process, together with the organisation of (and participation in) design teams. However, we assume that the Government will maintain some level of technical authority and expertise in order to act as a smart buyer. Table 2.2 summarises the types of technical and programme management skills that should reside within Government agencies, to

Table 2.2
Government Competencies

Technical Skills	Programme Management
Naval architecture	Finance
Mechanical engineering	General and programme management
Electrical engineering	Planning and production oversight
Structural engineering	Test and commissioning
Arrangements engineering	Design management
Signature analysis	Cost estimation
Fluids	Contracting
Systems engineering	
HVAC	
Combat and ship control systems	
Safety and operability	
Habitability	

adequately fulfill the role of smart buyer. It is evident from this list that the Government must maintain technical skills broadly similar to those of industry, in addition to programme management and oversight skills.

In addition to the above competencies, the Government capability must also include some number of uniformed (submarine-qualified) Navy personnel who bring an operational perspective to the design team.

Design Processes

Designing a submarine requires a unique mix of technical design and engineering disciplines, which often is not found in the broader maritime or naval industries (e.g., underwater hydrodynamics and acoustic propagation skills). Hull, mechanical and electrical (HM&E) aspects of the design require intense efforts and coordination by naval architects; hydrodynamics experts; and mechanical, structural, and electrical engineers to provide a platform design that meets speed, depth, and endurance requirements. Additionally, electronic systems engineers, computer scientists, and information technologists must coordinate their efforts to integrate information from the platform's sensors into a coherent picture so that a submarine's captain can make effective operational decisions.

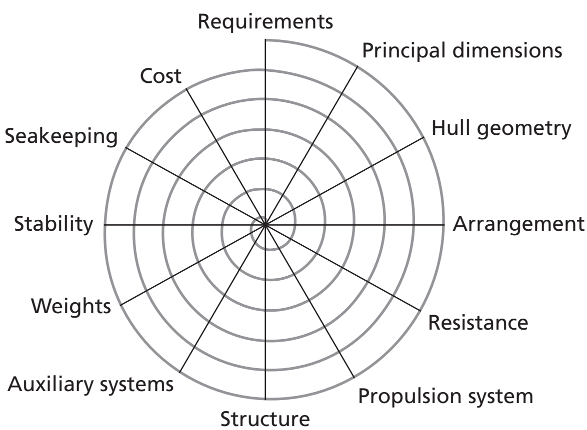
Yet the conduct and management of a submarine design programme does not differ significantly in objectives from any complex system. The goal of any design process is to deliver a product that meets the customer's operational and performance objectives at an appropriate cost and schedule. The products that are developed—both interim (e.g., arrangement models, block and single-line diagrams) and final (construction drawings, work packages, equipment procurement packages, manufacturing plans, logistics plans, maintenance plans, etc.)—are typically the same, irrespective of the design process used.

In 1959, Massachusetts Institute of Technology engineering professor J. H. Evans created the depiction of the ship design process shown in Figure 2.2.

The "spokes" in this spiral depiction represent design considerations, including performance requirements, vehicle characteristics and cost estimates. David Andrews refined the ship design spiral differently, as shown in Figure 2.3.

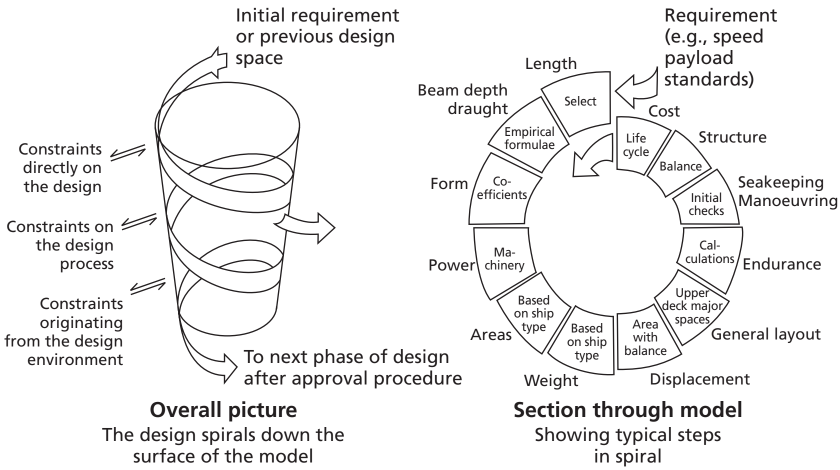
The loops of the spiral represent design iterations of increasing refinement as the design spirals in. The outer loop represents rough, sometimes parametric, estimates. Increasing precision of system and

Figure 2.2
Evans Depiction of the Ship Design Process



SOURCE: J. H. Evans, Basic Design Concepts, *Naval Engineers Journal*, Vol. 71, No. 4. Used with permission.
RAND *MG1033-2.2*

Figure 2.3
Andrews Depiction of the Ship Design Process



SOURCE: David Andrews, "Creative Ship Design, *Transactions of the Royal Institution of Naval Architects*, 1981. Used with permission.
RAND *MG1033-2.3*

sub-system descriptions occur as the process spirals in on the final design through subsequent iterations.

The design spiral starts with defined mission requirements that translate into performance requirements such as

- depth
- range
- speed
- sea state limits
- manoeuvring
- crew complement
- endurance
- payload

- specific system requirements
- safety features.

The first iteration in the design spiral develops arrangements of such items as the pressure hull, the hull envelope, and major components based on good design judgements. Then the geometry for the pressure hull (shape and dimensions) and the overall hull geometry envelope (shape, dimensions, volume) are developed, so that submerged and surface displacement calculations can be made.

A second iteration of the design spiral starts to develop details of systems and sub-systems and integrate them. Performance requirements are re-evaluated in light of first iteration results. This spiral continues until the design products necessary for building a ship are delivered to the building shipyard.

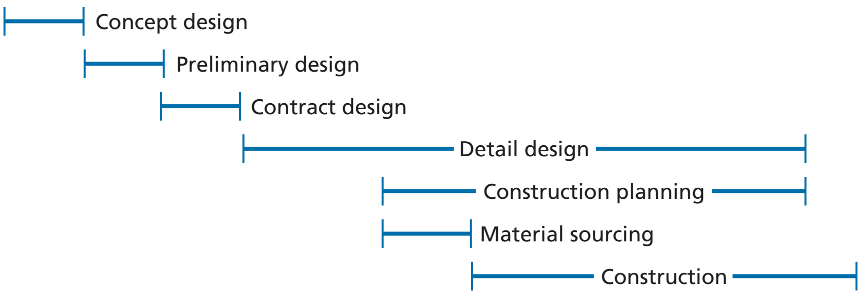
Approaches to Submarine Design

There are two basic design approaches: sequential and concurrent. In addition, organisations can tailor a hybrid design approach to suit their particular needs and interests.

Sequential Design Process

Traditional ship (and submarine) design is a sequential transition through several distinct phases of increasing design fidelity and complexity. As shown in Figure 2.4, sequential design involves four discrete, successive phases: concept design, preliminary design, contract design, and detail design. This figure is a broad representation of this

Figure 2.4
Sequential Design Process



RAND *MG1033-2.4*

process rather than an exact depiction; the process will vary slightly depending on how a specific programme is structured.

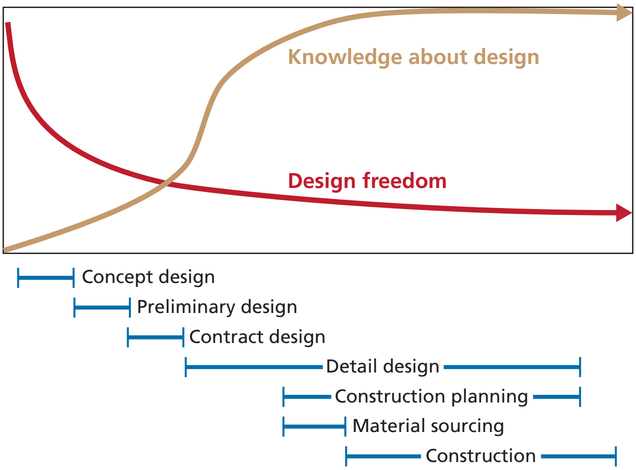
The idea of the sequential design process is to increase the level of knowledge of the design in a deliberate and orderly manner. However, as the design progresses and the level of knowledge accumulates, design freedom decreases. Particularly after award of the detail design contract, design freedom declines as elements of the design are decided. Figure 2.5 depicts the trade-off between design knowledge and design freedom as a function of time and progress through the sequential design phases.

The ideal approach is to increase knowledge of the design as early as possible, which creates opportunities to save time and costs (not just design cost, but also construction and maintenance costs) in the subsequent design phases.

Sequential Design Phase 1: Concept Design

During this initial step in the design process, future threats are examined, mission needs are defined, desired platform operational characteristics are explored, research and development efforts are proposed,

Figure 2.5
Cumulative Design Knowledge and Design Freedom During Phases of Design



RAND *MG1033-2.5*

and basic cost and schedule estimates are established. Whole-submarine concept design studies enable understanding of the effects and relationship amongst the numerous platform capabilities that are needed to address the desired submarine characteristics and their affect on programme cost and schedule.

The concept design phase has three objectives. First, it forms the basis to begin defining the performance and operational characteristics of the platform, thereby codifying the design requirements to be invoked later. Secondly, it identifies performance gaps in current technologies, which allows designers to define additional research and development efforts to mitigate the risk of missing some desired submarine capabilities. Finally, the concept design phase produces initial, rough-order-of-magnitude (ROM) cost and schedule assessments.

Concept design studies generally require a relatively small cadre of naval architects, arrangement and weight designers, ship system engineers, and cost engineers, all of whom are assisted by selected technology subject matter experts and ship operators. The actual number and skills needed are a function of the type of ship that is desired and the maturity and extent of technologies and capabilities planned for the vessel. Appropriate science and engineering experts perform technical gap analysis and define the research necessary to arrive at potential technical developmental solutions. For example, if a proton exchange membrane AIP system is desired but a naval, technical/operational requirement prohibits carrying stored hydrogen onboard a submarine, then a gap analysis may require sourcing a currently available reformer technology or, if that is unsuccessful, may mandate a new development programme.

Typical concept design expectations and products include a capability description, a statement of assumed operational concept(s), a description of potential material solutions, a ROM cost estimate, and risk assessments.[2]

Sequential Design Phase 2: Preliminary Design

Preliminary design starts with the output of concept design, which it uses to refine and firm up major system characteristics. It develops precise engineering definitions of mission systems to provide assurance that design elements will be delivered within the budgeted cost. It also initiates research and development on technology gaps when long development times are necessary to meet the overall programme schedule or to mitigate programme risks.

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[2] Risk assessments include risks associated with the concept (integration complexity, technology development, and requirements maturity), and risks associated with the study (detail design, design process, and analysis process).

Beginning with preliminary design and continuing through contract design, the design team must establish and agree on a set of design criteria.[3] In addition, the design team must address the technological constraints in the design.[4] The design team also must decide on the technical policies and philosophies that will guide it throughout subsequent design phases and during construction. Some typical technical policies and philosophies include safety, reliability, producibility, maintainability, acquisition cost, life-cycle costs, efficiency, simplicity of operation, and characteristics (weight, space, power, etc.).

Amongst other things, the preliminary design phase is expected to demonstrate that the design is balanced (using physics-based modelling), to ensure that the design is robust and takes into account risks and their potential disturbances, to confirm that the design is producible within the context of a given build strategy, and to execute risk-mitigation plans.

Sequential Design Phase 3: Contract Design

During the contract design phase, the government and contractors develop the contract specifications and drawings needed for companies to bid for detail design and construction. Efforts during this phase ensure that the design is balanced using physics-based modelling, that it is adjusted in response to problems (i.e., realised risks) and to changes in the build strategy, that the design has enough fidelity so

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[3] Design criteria include (1) established standards for design (military specifications; commercial codes, standards, and specifications; and local practice), (2) the level of conservatism to use in designing critical safety features (i.e., adequate design margin to limits or failure), and (3) testing and evaluation protocols for new technologies being employed that are critical to the design.

[4] Technological constraints include materials; structures; machinery and equipment; energy sources and conversion; propulsion and manoeuvring; control, communications, and computer data processing; navigation and positioning; and life support and habitability.

that any remaining degrees of freedom within one construction unit do not impact other construction units, and that risk-mitigation plans are executed.

This phase traditionally produces a set of detailed ship specifications; contract drawings (which include hull lines and offsets); a primary structural profile of the pressure hull and overall, two-dimensional general plan view arrangement of the platform; arrangement elevation and arrangement sections data; a naval architectural weight and balance summary; and arrangement drawings.

Sequential Design Phase 4: Detail Design

The primary objective of the detail design process is to integrate contractual requirements, specifications, engineering inputs, and to design build requirements to produce an efficiently executed ship design. This phase develops construction drawings and plans necessary for a competent builder to acquire material, plan construction, and build the submarine.

This means that final arrangements need to be sufficiently mature and complete prior to the start of fabrication/construction. Sufficiently mature drawings must be sequenced to support procurement, production planning, and fabrication start. Moreover, the production design must support ship construction needs, which sometimes requires that design products be validated through a series of build plan reviews and construction pilots.

The detail design must adjust the design in response to problems and the particular build strategy of the construction shipyard. The detail designers should use physics-based modelling and/or full-scale testing, as needed, to confirm that the design meets requirements.

Continuing Support to Construction

The requirement for design resources does not end with the completion of the detailed design phase. Draftsmen and engineers at the design organisation or design agent continue to support the construction of the platform through the total build of the class. Often, modifications to the initial designs are needed to correct errors found during construction, to address new missions or new equipment, to support manufacturing process changes, or to reduce building costs.

Just as important, government personnel also are needed during construction to work with the design organisation and/or builder on design changes and to oversee the contractual processes. They also monitor the construction of the platform to ensure that it meets all requirements and can operate safely.

Sequential Design Pros and Cons

Traditionally, the four phases of the design process (concept, preliminary, contract, and detail) are conducted in a lock-step manner, with a period between each phase during which decisions on whether and how to proceed with the overall design programme are made. The rationale behind sequential design is to divide large, complex efforts into discrete, manageable efforts. This approach has the benefit of providing time for the government to make decisions before a programme advances to its next development stage.

However, one drawback of this approach can be continuous design revisions. The process begins with draftsmen proposing a design solution. Then procurement experts sub-contract design and/or manufacture of required material and components. The feedback from component developers often indicates performance shortfalls, and new component development is proposed or the ship design is modified to take advantage of alternate components or technology. Logistics personnel then perform a review. Once again, a series of negotiations takes place and design revisions and re-approvals occur. At some point, the end user is invited to see the product and provide expertise and comments on the man-machine interface, human system integration, and life-cycle maintenance. Once again, comments are generated and the design is revised. Finally, production personnel review the design and a further series of negotiations takes place to modify the design to facilitate production.

As fidelity increases, additional reviewers address other areas, such as environmental issues, training, and safety. At each step, the potential to discover a new flaw exists, the resolution of which requires redesign. Complicating the effort, external technical reviewing authorities often require mutually exclusive design solutions. Because they have no ownership of the design, these reviewing authorities have no incentive to compromise or accept risk and view themselves as gatekeepers of technical purity. Consequently, delays and disruptions may arise as multiple layers of senior decision-makers become involved in resolving issues.

Significant drivers behind higher risks and costs in ship acquisition are the multiple redesigns of previously designed portions, motivated by the need to either (1) accommodate requirements changes initiated late in the design by the customer, the technical authority, or the manufacturer or (2) address flaws that need to be resolved at the design contractor level. The later in the process these events occur, the more costly the resolutions as ever-more detailed drawings are affected. Design flaws found during construction and test are the most costly of all to correct.

A second and intentional trait of the sequential design process is the need to complete each phase in sequence before starting the following phase. For example, the contract design tasks do not start until all preliminary design efforts are completed. This approach generally stops work in selected areas to wait for critical decisions to be made, which can lead to staffing issues for specific skill sets as well as unintentional lengthening of the design process.

These clearly defined stopping points can be advantageous to customers, allowing them to perform a holistic review of the design at some known level of fidelity. However, the intermediate intervals between design phases can delay the design process, disrupt the workforce, and often result in changes to requirements or preferred approaches to a design solution. Any such changes become increasingly disruptive and costly as the design stages progress.

Moreover, design products for use in a competitive award of a subsequent design or construction contract will be generic and not optimised for any one contractor. Intellectual property and competitive advantage concerns may also keep a set of draftsmen from disclosing their best ideas to the customer in these pre-competition design products. Similarly, intellectual property concerns may prevent collaboration between prospective competitors, reducing the pool of skilled resources available to work on the early stages of the design process.[5]

Table 2.3 summarises some advantages and disadvantages of sequential design.

Concurrent Design Process

To overcome some of the limitations of the sequential design process, some organisations have adopted a concurrent engineering process

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[5] In the United States, the *Los Angeles*–class submarines were non-competitively designed using the sequential design process. The *Seawolf*-class submarines were competitively designed using the sequential process. The *Virginia*-class submarines were non-competitively designed using a concurrent design process. While the *Los Angeles*–class submarines were not as capable or complicated as the other two classes, they were designed and constructed in the shortest period of time—approximately seven years shorter than either of the other two classes.

Table 2.3
Advantages and Disadvantages of Sequential Design Process

Advantages	Disadvantages
Clearly defined review points	May result in longer design times
Workforce demands more evenly spread with time	Prone to greater levels of rework
Clear organisational responsibility during each phase	"Throw it over the fence" mentality between designers, suppliers, builders, and customer
Clear points to hold competitions	Minimal participation from manufacturing, operations, test, and support communities
	Difficult to keep workload uniform over design

wherein discrete, sequential design phases overlap. That is, the last three phases of the design process—preliminary, contract, and detail—are performed in a seamless manner without the start-and-stop events of the sequential design process. This concurrent process may be inherently more manpower- and resource-intensive because more design work is being performed at any given time in the phases of design.

One advantage of this approach, however, is that problems often surface earlier and are resolved more collaboratively at a juncture when it is less expensive to make changes.[6]

The advantages of incorporating a collaborative approach that includes industry, end users, and others at the beginning of the concurrent design process has evolved into what is called *Integrated Product and Process Development* (IPPD). IPPD merges many stakeholders

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6 Three cost axioms of submarine design: (1) Most of the future construction and maintenance costs to be incurred are locked into the design in the early part of the effort; (2) the cost to make a change is lowest in the early part of the design effort and increases proportionally as the design matures; and (3) changes made during construction are the most costly.

earlier in the design process. IPPD processes balance the complexity, breadth of technical skills required, duration of design effort, and cost sensitivity to schedule disruption for extremely complex aircraft and ship programmes. The approach begins with the end in mind and folds in all aspects of the product life cycle (e.g., production, procurement, test and evaluation, support). It considers more than just the design outputs; it also takes into account such issues as manufacturability and supportability, thereby reducing changes later in the design, build, and maintenance of a product.

IPPD has demonstrated significant improvements and efficiencies in the delivery of complex multi-disciplined products within cost and schedule constraints. Its successes include programmes ranging from the Boeing 777 and F-18 E/F fighter acquisition to the *Virginia*-class submarine. Boeing, for example, cites a reduction in cycle time of 17 percent and a reduction in rework of 40 percent.[7]

In the same vein, Electric Boat reported in 2002,

> Problems identified during construction are far fewer and less serious for VIRGINIA than SEAWOLF . . . as of the end of January 2002, 3.2 years after construction start, the VIRGINIA builders had identified about 5,300 problems. As a fraction of labor hours required to build the ship, VIRGINIA had reached almost 70 percent. SEAWOLF did not reach that level of construction completeness until almost six years into the build. At that time, SEAWOLF's builders had identified about 53,700 problems. So,

[7] Gary Brown and Cliff Harris, "Matching Product Development Practices to the Product Life Cycle", *Highlights of the Thirty-Fifth Advanced Manufacturing Forum,* Center for the Management of Technological and Organizational Change (CMTOC), February 27–March 1, 1995.

the reduction in errors at comparable points of completion is about 90 percent.[8]

Electric Boat also showed a negligible growth in man-hours at completion for *Virginia*, compared to 77 percent for *Seawolf* and 60 percent for *Ohio*.[9] However, the 2002 Electric Boat report acknowledged that the experience gained in designing and building *Seawolf*, in addition to the IPPD approach, contributed to many of the improvements in design and construction efficiency seen on *Virginia*. For example, the heavy computational analysis and testing performed on *Seawolf* to improve its acoustic signature were rolled over into *Virginia*. In another example, significant pressure hull technical welding problems were resolved on *Seawolf*, which took several years, so that they did not occur at all on *Virginia*. Experience from the *Collins*, to the degree that it is transferable after a construction break of 20 years, will likely result in design and construction efficiencies for the Future Submarine.

In concurrent design processes that incorporate IPPD, many of the tasks within the traditional preliminary, contract, and detail design phases are performed in a parallel and seamless manner, with the shipbuilder and the government participating in all phases of the design process. Stakeholders outside the typical design team (e.g., manufacturing and operations) also are represented during the design process.

A concurrent design approach using IPPD starts with a systems definition phase followed by an integrated design/construction planning development phase as shown notionally in Figure 2.6. In actuality, the phase start and end points are blurred and can overlap, but

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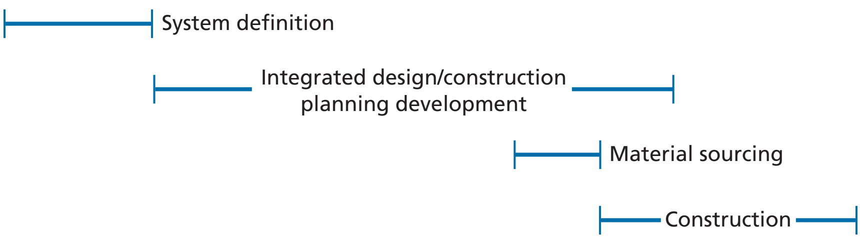
8 General Dynamics Electric Boat, *The VIRGINIA-class Submarine Program: A Case Study,* February 2002, p. 69.

9 General Dynamics Electric Boat, 2002, p. 17.

Figure 2.6
The Concurrent Design Process with IPPD



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for ease of viewing we depict the process in a simplified manner. This change better integrates design and production planning while ensuring that the life cycle of the platform is considered at every stage of development. This process has led to design completion much earlier than has the traditional sequential process.

An important aspect of concurrent design approach using IPPD is the design/build/support approach. This philosophy integrates individuals who are knowledgeable about the construction and in-service support processes into the design teams. Bringing construction and in-service support expertise to bear early in the design process can minimise the type of costly rework during construction that results from a mismatch between what designers desire and what builders and maintainers can efficiently build and support. The result is far fewer design changes during construction.

Design/build/support is, at its simplest, an industry-driven, system-engineering process established to deliver a product. At its core, it encompasses a team-based design philosophy that is driven by integrated, multi-disciplinary teams, preferably co-located, that are wholly accountable for the cost and technical quality of the product.

Table 2.4 summarises some advantages and disadvantages of the concurrent design approach using IPPD.

Table 2.4
Advantages and Disadvantages of Concurrent Design Process That Includes IPPD Processes

Advantages	Disadvantages
Shorter design-cycle times	Lack of clear review points
Less design rework	Highly concentrated workforce demands
Collaborative process encompassing several stakeholders	Challenging programme management
Better manufacturability	Difficult to have production competition after collaboration in design
Potential to decrease lead ship and recurring construction costs	Need for co-located teams
Potential to decrease maintenance costs	Government must provide timely input
	Increases up-front non-recurring design costs. The design funding profile must be front-end loaded.
	Requirement to pick builder at same time as designer

For more information on implementing a concurrent design process that includes IPPD, see Appendix C.

Hybrid Design Process

Some organisations have adopted a hybrid design process to eliminate problems associated with the sequential design process and to take advantage of the better parts of the concurrent design approach using IPPD. The hybrid process is a risk-based approach that retains clearly defined decision gates while allowing risky aspects of the design to proceed at a faster pace.

For example, because of the integration issues with emerging AIP technology, power storage, propulsion train, etc., the propulsion plant in a contemporary conventional submarine may take longer to develop and may contain a number of technical and schedule risks. In some areas the rate of change in propulsion plant technology is much slower than in other systems of the submarine. In a hybrid process, once the preliminary design is complete and the submarine's key parameters (size, estimated maximum speed, depth, acoustic signatures, amongst others) are well defined, decision-makers may permit the propulsion plant to proceed as quickly as possible. A competition can be held to select a propulsion plant contractor, if desired.[10] In other words, in the hybrid approach the propulsion plant develops concurrently and seamlessly, as it would in a concurrent design approach. Similarly, since the rate of change of technology for torpedoes and other submarine-based weapons is relatively slow, as are the mechanical systems that stow and launch them, their development can proceed in a manner similar to the propulsion plant, provided that identified risks have appropriate mitigation plans in place.

On the other hand, a hybrid design process would typically delay such decisions as the command and control system because the rate of change in that technology is much more rapid. Under those circumstances, competition for the latest architecture and technology may be desirable. The command and control system would follow the sequential design process.

Note, however, that each major system that is a candidate for the hybrid/seamless process may represent a potential constraint on the rest

[10] This includes the design and manufacture of ready-to-install propulsion plant components and sub-systems scheduled in time to support efficient overall ship construction.

of the design at a later time. Each major system of the submarine (e.g., propulsion, command and control, combat weapons system, sonar acoustic sub-system) must pass a decision gate. These gates may align with the milestones noted by the beginning and ends of the traditional design phases. Typically, they do not. They are event-driven gates much like those in the concurrent design process.

To implement the hybrid design process efficiently, a major decision as to which company or organisation will be the design integrator needs to be made early. This decision can be difficult. The term *design integrator* amplifies the primary function of this organisation. Although the design integrator (or platform contractor or design agent) may be selected early with little technical or commercial basis for competition, it will be required to run competitions for all the major systems as directed by the government and in accordance with government regulations and statutes.

Additionally, the hybrid design process may desire to "begin with the end in mind". In this context, the design integrator would seek out key stakeholders in government and industry and obtain their input in a less formal manner than in a fully developed IPPD process.

Table 2.5 summarises some advantages and disadvantages of the hybrid design approach.

Selecting a Design Process

The selection of the best design process for any organisation and programme depends upon several factors:

- The experience level of the design organisation's management. Although a seamless IPPD approach can provide significant benefits to a programme, it is a daunting management challenge. If

Table 2.5
Advantages and Disadvantages of a Hybrid Design Process

Advantages	Disadvantages
Clearly defined review points	More design constraints
Workforce demands more evenly spread with time	Government must provide timely input
Clear organisational responsibility during each phase	Difficult to keep workload uniform over the design period
Clear points at which to hold competitions	Requires selecting design integrator up front
Collaborative process encompassing several stakeholders	
Better manufacturability	
Potential to decrease recurring construction costs	
The hybrid approach requires more manpower and money early in the design effort than the sequential approach but less manpower and money than the concurrent approach—hence the hybrid nature of this approach	
Risk-based decisions are made	

the design organisation does not have sufficient personnel with significant complex design experience, chaos could result, with a detrimental impact on the programme.

- The willingness to select design and/or construction contractors early. IPPD requires the builder to be involved with the design team from the outset. This precludes competition for construction when design details are firm enough to conduct a meaningful price competition.

- The availability of up-front funding. Because the seamless IPPD approach involves production, maintenance, and supplier personnel early in the process, it requires more funding up front than the sequential process does.

Roles and Responsibilities

A primary consideration in the Future Submarine design effort will be the roles and responsibilities that each participant maintains. While current plans call for an industry/Government partnership with assistance from allies, many decisions that will affect personnel resource requirements remain. Specific areas in which Australia will need to develop an organic capability will become clearer as negotiations on intellectual property and other agreements between countries and corporations proceed.

Other decisions, such as the level of oversight desired on the part of the Government and the role of the platform contractor, will affect the number of individuals required to support the design effort. As agents of the public trust, the Government is responsible for managing the programme so that the cost, schedule, and scope of the project meet Government objectives.

A number of choices must be made to ensure the public trust. Particularly challenging is making sure that the programme adheres to established technical, operational, and safety objectives. If the Government is to perform this function directly, significant technical resources and expertise will be needed. Hiring large numbers of Government employees to perform these duties may commit the Government to long-term employment that may not be in its best interest. Alternatively, the Government could hire a smaller number of Government engineers and design authority to perform this function on behalf of the Government. This design authority should be independent from any contractor performing any of the design or manufacturing/construction of the submarine and objective in its reasoning as it reviews design and construction deliverables. A team composed of a cadre of Government engineers and the design authority contractor would perform the technical authority function. The design authority would be organisationally separate and independent of the platform contractor/design agent (the organisation actually responsible for executing the design, including the major system procurements and developing the construction work packages). However, Government engineers, the design authority, and the design agent should work hand-in-hand with the common object of ensuring programme success. In either case, the Government retains the ultimate authority for cost, schedule, and scope objectives; it also accepts the associated risks.

Government

The evolution towards privatisation of various technical and managerial functions within the shipbuilding industry has occurred in many countries, including the United States, the UK, and Australia. In some instances, the decision to divest government expertise has resulted in unacceptable outcomes, such as significant cost and schedule growth or inadequate development of desired capabilities.[11] These unacceptable outcomes and increasing concern over the appropriate role and level of government involvement in defence acquisition prompted a study of this issue. A RAND report on the UK Ministry of Defence's (MoD's) roles and required technical resources for the UK submarine indus-

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[11] See John F. Schank, Cynthia R. Cook, Robert Murphy, James Chiesa, Hans Pung, and John Birkler, *The United Kingdom's Nuclear Submarine Industrial Base.* Vol. 2, *Ministry of Defence Roles and Required Technical Resources*, Santa Monica, Calif.: RAND Corporation, MG-326/2-MOD, 2005.

trial base argued that best commercial practices support a partnership model in which government and industry are partners throughout the acquisition process.[12] This research suggests that the government should maintain certain functions that are required to manage the technical and other programme risks and to act as a "smart buyer". These functions include programme management, technical oversight and authority, and support of research and development and component design (as required), especially in highly specialised areas where there is insufficient commercial basis to sustain the specialty over a long period of time.

Technical authority is required to ensure a safe submarine design. The government should have a final technical adjudication as to whether design elements adhere to established technical standards and policy. This technical adjudication must concern not only individual elements of the design but also the interaction of individual elements as they aggregate to larger systems and structures. To be effective, this technical adjudication must be independent to ensure the maintenance of technical standards in the face of project schedule or cost-savings demands.

As the end user of the submarine design, the Australian Government must ensure that the design efficiently meets its programme requirements. In a sequential design approach, the Defence Materiel Organisation (DMO) can either be heavily involved in the design process, effectively designing the submarine itself, or can undertake periodic detailed and painstaking reviews of the physical mock-up and developing design products.

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[12] Each partner takes a leading or following role, depending upon the acquisition phase. This research suggests that the Government should have the capability to lead the requirements generation, to be a leading partner with industry on the concept development, and to be a follow partner on the detail design of the boat. See Schank et al., 2005.

In the concurrent design approach, Government personnel must be part of the design team, providing continuous feedback as the design is evolving.[13] This collaborative approach minimises design rework and enables the Government to ensure that programme requirements are met in the most effective and timely manner, but it requires a greater level of resident Government technical expertise. Alternatively, if a hybrid approach is used, a smaller number of DMO engineers, design authority engineers, and other personnel can work closely with the design agent. Ideally, the DMO personnel actively control the operations of the design authority contractor.

Taking an active role in developing the design is not the only function that the Government must play to ensure that the design efficiently meets its programme requirements. Also needed is a rigorous testing programme. Such a testing programme not only ensures that a submarine meets requirements, it also provides important feedback to the design process, allowing design changes to be made for subsequent ships built using the same design. The design authority should initiate the development of such a testing programme and oversee its execution.

The Government also will need to establish the extent of the submarine safety criteria. Safety may be limited to preventing and recovering flooding, or it may be more extensive and address the gamut of safety-related issues—depth excursions, control system failures, fires, atmosphere contaminates, high-temperature pressure fluid systems, etc. For example, submarine safety in the United States refers only to keeping water out of the pressure hull and to surfacing safely should water get inside the pressure hull.[14] Other safety aspects, such

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[13] Robert Winner, *Integrated Product/Process Development in the New Attack Submarine Program: A Case Study;* 2nd ed., R. Winner and Associates, February 2000, p. 2.

[14] Sometimes referred to as SUBSAFE.

as fire, atmosphere toxins, and crew safety, are covered under other less regimented processes. In the UK a different approach is taken and is referred to as the whole-boat safety case.

If the Government does not wish to maintain the required technical acumen, does not possess requisite past experience, or has no desire to develop design rules and process documents related to safety criteria, it can turn to independent third parties that can produce pre-packaged ship design and construction rules.[15] Like the testing programme, the design authority should initiate development of the submarine safety criteria and oversee their execution.

The Government may have to be responsible for maintaining or developing some of the technology base that the Future Submarine programme requires or will require. This includes research and development (R&D) activities that are not performed by industry but that are germane to current and future submarine capabilities. There may be submarine components of such a nature that the Government retains responsibility for their development. This includes designing and developing components for which there is insufficient demand to sustain an industrial base but that are critical to the submarine or are required for the integration and interoperability of certain systems.[16] Additionally, the Government might have to maintain testing facilities that are required in the submarine design process but are not commercially viable for private industry.

In summary, the Government should play the primary role in requirements development, ensuring that the design efficiently meets its programme requirements. It should do this by establishing safety criteria and a testing programme; engaging in programme manage-

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15 See Appendix A for further discussion of safety issues.

16 In the United States, this includes integration and interoperability of the command, control, communications, computers, and intelligence (C4I) and combat control systems.

ment and oversight; and maintaining capabilities not supported by industry, such as specialised component design or R&D programmes.

Industry

The level of technical responsibility taken on by industry will ultimately depend upon the role the Government plays in the design process. The *Defence White Paper 2009* identifies many potential opportunities for industry, including platform contractor/design agent and vendor/supplier.[17]

Typically, the platform contractor/design agent is responsible for having the requisite skills and expertise to refine a specified concept in sufficient technical detail so that a constructible submarine results. The customer, in this case DMO as a representative of the Commonwealth, provides information on desired capabilities and characteristics of the vessel. The platform contractor then turns the concept into increasingly detailed drawings and models for review by the customer. The platform contractor is responsible for managing the cost and schedule of the design programme. The platform contractor is typically responsible for *integrating* systems and components, not necessarily designing all of them. The platform contractor should elicit the experience and expertise of component suppliers or other vendors. The platform contractor/design agent could procure the services, components, and systems competitively so that the best value is obtained. For example, the platform contractor may subcontract combat systems design and development, retaining the integration of the combat systems into the submarine. The platform contractor likewise may subcontract the whole propulsion plant or significant portions of it to reduce programme risk.

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[17] The *Defence White Paper 2009* identifies design, modelling and simulation, project management, R&D, and system definition and development as activities in which industry may participate.

A number of vendors or component suppliers may support the design effort.[18] Specialist vendors and suppliers typically provide subsystem capabilities not maintained by the platform contractor or the Government. These capabilities may be too expensive for the platform contractor to maintain in-house or to develop independently. Similarly, the suppliers might have on their staffs technical and manufacturing specialists whom the shipbuilders would have difficulty keeping steadily employed.

Other Factors Influencing Design Workload

The Future Submarine programme is in its infancy, and nearly all key design decisions about it or how it will interleave with the *Collins* have yet to be made. Many of these decisions could have a significant impact on the design workload in industry and Government. For example, a decision on hull-life expiry of the *Collins* (hence, when the first submarine in the new class is to be required) may set the desired duration of the design effort.

As noted previously, setting the roles and responsibilities of industry and Government is a decision that will affect the distribution of tasks and thus the workload required by industry and Government personnel. Setting the technical and operational requirements for the new submarine is another decision with a direct impact on the total man-hours required to complete the design effort.

Another influential decision that will affect the shape of the demand curve for different skills (and probably the total man-hours

[18] In the United States, suppliers constitute roughly half of the total procurement cost for a submarine through government furnished equipment (GFE), contractor-furnished equipment (CFE), and contractor-furnished material (CFM).

required for the design effort) is the specific design process (sequential, concurrent, or hybrid) that the programme will use. Specifying the level of detail in the design drawings is a further decision that can change the demand for draftsmen as well as the shape of the demand curve.[19]

Last but not least, a decision on whether to design or to buy major equipment and components will impact the total man-hours needed for different skills, the duration of the project, and the shape of the demand curve for specific skills.

Design Skills and Processes: Conclusions

Designing a modern submarine is a complex process that requires a large and broad mix of highly skilled competencies and skill sets in both industry and government. For this analysis, we have described a set of 17 technical competencies in industry that we believe can be used as a framework for articulating the personnel needed to design a modern conventional submarine. They engage in a spiral process that increases knowledge of the vessel over time while concurrently losing design freedom as the vessel becomes better defined.

We also described two categories of skills that government personnel need to oversee the design of a modern submarine: technical skills and management skills.

Industry and Government personnel can use one of three processes to design a submarine: sequential, concurrent, or a hybrid of the

[19] The decision here may be influenced by the proficiency of the Australian submarine production base (which may be low due to the gap between the build of the last *Collins*-class boat and the start of the new submarine's construction) and the availability of experienced submarine draftsmen in Australia.

two. Because each approach has distinct advantages and disadvantages, the programme office will have to decide which is best for the Future Submarine based on prevailing circumstances in Australia. In part, such a choice will depend on the degree to which

- the Future Submarine uses existing system and component designs
- the Government seeks to participate in the detailed design in addition to managing the design process
- industry is experienced and comfortable with each process
- the design workforce is available at the appropriate time and in the appropriate numbers.

As the end user of the design product, the Government must ensure that the design efficiently meets its requirements. This means that the Government must act as a smart, technically savvy buyer.

CHAPTER THREE

Predictions of Future Demand: Estimates of Manpower Required to Design the Future Submarine

The proprietary data that we gathered on the manpower required to design the *Upholder* and *Collins* classes underpin our understanding of the manpower demands that are required to design a submarine in the modern era. However, because those historical data do not deal with a submarine of the technical complexity, capability, and size of the Future Submarine, the RAND project team determined that the data needed to be adjusted to more realistically reflect the programme's objectives.

To make these data adjustments, we first turned to a panel of submarine experts with decades of experience designing and managing submarine programmes for multiple governments and industrial firms. These experts used the skill categories from Chapter Two to derive first-order projections of the total man-hours that would be required to design the Future Submarine. Each expert provided one or several point forecasts (i.e., a single value) of the man-hour total that the expert estimated the programme would require.

The RAND team then used those point estimates to develop a range of estimates. The team has significant experience in numerous submarine and ship design studies for the United States and the UK. This experience strongly suggested that high levels of uncertainty surrounded the Future Submarine programme and stemmed from the numerous key design and acquisition decisions that have yet to be made. As a consequence, a range of estimates for the required design effort, rather than a single estimate, would better portray the level of demand.

The RAND team went on to compare its man-hour estimates and the experts' single point estimates with data submitted in 2009 by several European submarine design companies in response to the Commonwealth's request for information on their capabilities to design the Future Submarine. Those submissions contained information about the level of effort that the companies anticipated they would require to design the vessel.

Even though we show demand spanning a range, we caution readers not to be misled by any precision that the numbers imply. The numbers are rough-order-of-magnitude (ROM) estimates of man-hours, which can and will be affected by many internal and external factors. We discuss these factors throughout this chapter.

Point Estimates of Demand: Projections Derived from Experienced Submarine Design Experts

Our panel of experts included several senior submarine designers with considerable programme management experience in conventional and nuclear-powered submarines. They applied their experience to estimate the manpower needed to design a conventional submarine along the lines of the *Collins* class but with evolutionary improvements.

To make their estimates, the experts considered the factors displayed in Table 3.1, which are elements associated with the design of a modern diesel submarine such as the Future Submarine. They used these factors to estimate the degree to which

Table 3.1
Factors Considered by Experienced Submarine Design Experts

Requirements	Technical design requirements	Specifications
		Design standards
		Design codes
		Certification
	Performance	Speed
		Depth
		Firepower
		Endurance
		Combat system
		Acoustics
		Shock
Complexity		Design
		Production
		Modernisation
		How one deals with the complexity
Density		Weight limited
		Volume limited
		As small as possible
		Allowances for efficient maintenance
Workforce experience		Whole submarine design planning
		Whole submarine design integration
		Submarine arrangements
		Structural design
		System design

Table 3.1—Continued

Workforce experience	Component design
	System analysis suitable for a capable modern submarine
	Work package development
	Procurement specification development
	Production process development and qualification
Diesel electric versus nuclear power	Required level of quality assurance
	Total number of systems and components to be designed
Design process	Sequential
	Concurrent
	Hybrid
Risk	Technology
	Design processes

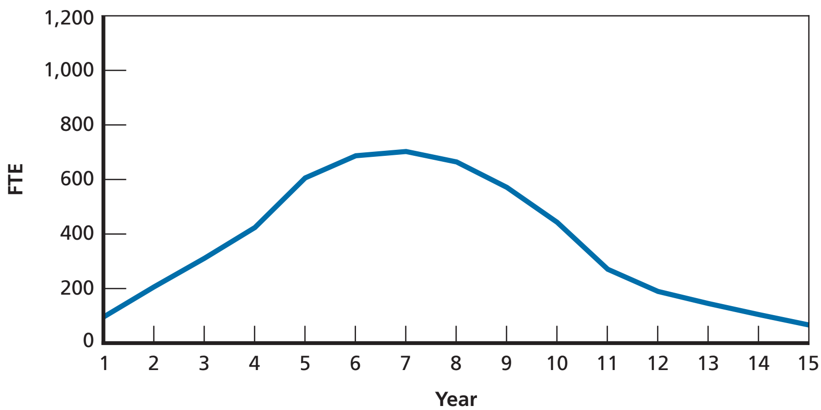
the level of effort to design the Future Submarine might exceed or fall short of known levels of effort to perform similar tasks in designing a typical nuclear-powered submarine in the United States. This allowed the experts to estimate demand for the Future Submarine by working backwards from the known and established manpower levels associated with designing a typical U.S. nuclear-powered submarine.

The experts' calculations were relatively straightforward. In simple terms, they assigned mathematical weights to each factor in Table 3.1.

A weight of 1.0, for example, meant that the manpower demands for the Future Submarine were predicted to be the same as that for a typical nuclear-powered submarine. On the other hand, weights of 1.05 or 0.85 meant that the manpower demands were forecast to be 5 percent greater or 15 percent less, respectively, than those required to design a nuclear-powered submarine.

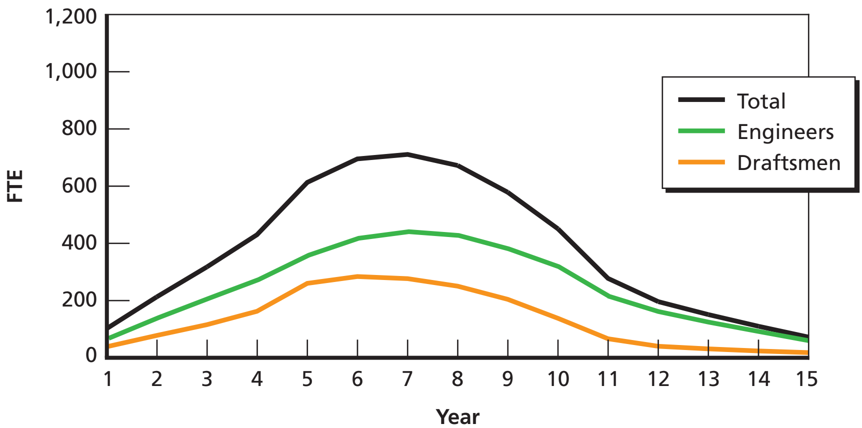
Figure 3.1 displays one expert's estimate of the total number of hours that would be required to design the Future Submarine. He estimated that the programme would require a design effort totalling 9.4 million man-hours (MMH) over 15 years and a peak personnel headcount close to 700. Figure 3.2 breaks out that total into draftsmen and engineers.

Figure 3.1
One Expert's Estimate of Number of Full-Time Equivalent (FTE) Personnel Required by Industry to Design a Large, Conventional Submarine, by Year (15-Year, 9.4-MMH Design Effort)



RAND *MG1033-3.1*

Figure 3.2
One Expert's Estimate of Number of FTE Draftsmen and Engineers Required by Industry to Design a Large, Conventional Submarine, by Year (15-Year, 9.4-MMH Design Effort)



RAND *MG1033-3.2*

Range Estimates: Demand Projections Produced by RAND

As noted previously, high levels of uncertainty exist surrounding the Future Submarine programme that are related to a host of key design and acquisition decisions that the Australian Government has not yet made.[1] Clearly, at this stage in the Future Submarine programme,

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[1] These decisions include defining the roles and responsibilities of Government and how they will be accomplished; defining the roles and responsibilities of industry; establishing desired performance parameters, e.g., range, endurance, quieting; determining the level of development required—evolutionary versus revolutionary; determining MOTS/COTS utilisation versus developing new major components and systems to meet the technical specifi-

these fundamental decisions are premature. Given such uncertainties, we determined that providing estimates of demand that fall within a range would be more realistic than providing a point estimate. Consequently, we developed lower- and upper-level estimates of the demand for the industry personnel required to design the Future Submarine. We derived these estimates from (1) the historical proprietary data that we report in the companion Commercial-In-Confidence monograph to this study and (2) our estimates of the workload that we expect will be involved in fulfilling new design criteria in the Future Submarine programme, such as its expected propulsion system and its larger displacement relative to the *Collins*-class vessels.[2] Table 3.2 summarises the differences in assumptions between the lower-level and upper-level estimates.

For both levels of effort, we assume that the Future Submarine will be a new design and that the first submarine will be delivered approximately 15 years from commencement of the design process (i.e., approximately 2025) to replace the *Collins*. The desired increase in operational performance and capability will likely lead to a larger and more complex submarine than the *Collins*. We assume that the duration of the design effort will be 15 years and that the workload will follow an approximately normal distribution. We assume the Government is responsible for the management of the programme so that

cations; determining the design process to be employed—sequential, concurrent, or hybrid; and determining the level of detail required in drawings and exact nature of required design deliverables, e.g., delivery of the three-dimensional model, work packages, drawings.

2 The Future Submarine is expected to have a 4,000–4,500-tonne displacement, compared with the *Collins* class's 3,300 tonnes. To make their estimates, RAND researchers drew from the *Upholder* and *Collins* experience, from the estimates made by the submarine experts involved in this project, and from lessons RAND learned working on other submarine projects for the United States and the UK. The experts' estimates, on the other hand, were largely extrapolations from their individual experiences working on U.S. and Taiwanese programs.

Table 3.2
Factors Leading to a Lower or Greater Level of Effort

Decision Factor	Lower Level of Effort	Greater Level of Effort
Performance requirements of the next submarine	Similar to *Collins* class	Improved from *Collins* class
Desired technology	Fully developed	Requires development
Type of design	Evolutionary	Revolutionary
Detail in drawings and design deliverables	UK model[a]	U.S. model[b]
Design workforce experience	High	Low
Design complexity	Low	High
Design integration	Low	High
Design data re-use	High	Low
Technological transfer from offshore	High	Low
Use of foreign design done either offshore or in-country	High	Low

[a] The construction shipbuilder will have interpretive power in design implementation (i.e., less detail design), and design deliverables will contain minimal detail.

[b] The construction shipbuilder will have little interpretive power in design implementation (i.e., more detail design), and design deliverables will be fully detailed. For example, every weld is uniquely rather than typically specified. Another example is that every pipe-fitting is specific—the designer is not referred to a standard valve, flange, and fitting schedule. The estimate is based on providing direct feed to numerical-controlled machinery. It includes providing manufacturing process-engineering data, including fixtures, digital work packages, procurement sketches, and test facility drawings.

the cost, schedule, and scope of the project meet stated objectives. We further assume that industry is responsible for providing the design in sufficient technical detail to construct the desired submarine and to assist as needed during submarine construction. Additionally, we assume that the major systems on the new submarine, including the propulsion/power train and the combat system, will be provided by major international vendors.

Decisions that could drive the total workload to the lower end include less challenging operational performance and capabilities, the use of a concurrent design process, and including less detail in the drawing produced for construction. On the other hand, more challenging operational performance and capabilities, the use of a sequential design process, and more detail in the construction drawings could result in a total workload approaching the upper bound.

RAND Estimate of Overall Industry Level of Effort

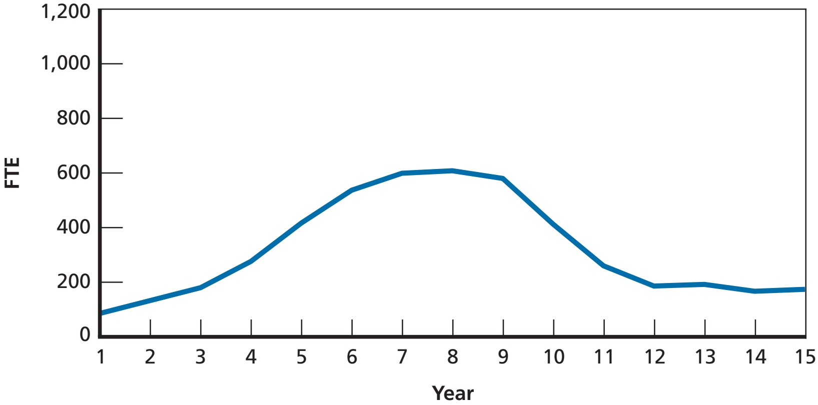
Based on the above assumptions, we estimate designing a large conventional submarine such as the Future Submarine in Australia would require an industry design effort of between 8 MMH[3] and 12 MMH.[4] Figures 3.3 and 3.4 display the total man-hour curves and line graphs for the estimated demand at the 8 MMH level. Figures 3.5 and 3.6 show similar displays for the 12 MMH estimate.

In all of these figures, it is important to note the rate of buildup for the design workforce, or the upward slope of the curves. If the Commonwealth cannot achieve these rates, the programme will not

[3] The estimate includes 1.5 MMH for risk-reduction design work required to demonstrate new concepts.

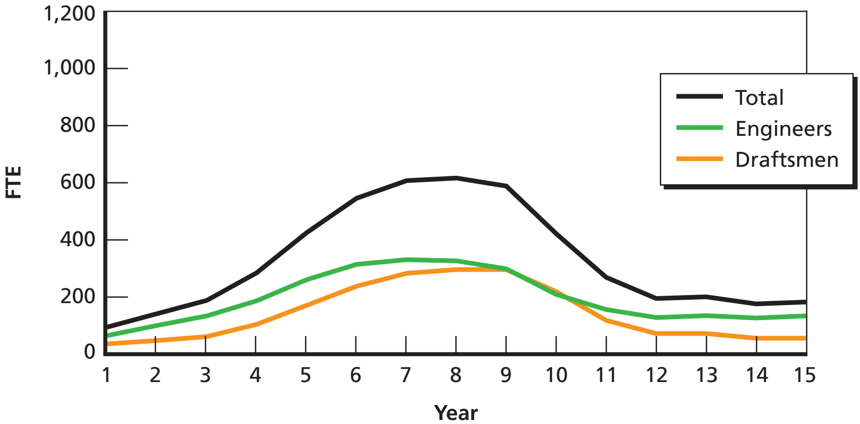
[4] The estimate includes 1.5 MMH of design for production planning, work package development, and component procurement specification preparation normally performed by the lead ship builder and 2 MMH for risk-reduction design work required to demonstrate new concepts.

Figure 3.3
RAND Estimate of Number of FTE Personnel Required by Industry to Design a Large, Conventional Submarine, by Year (15-Year, 8-MMH Design Effort)



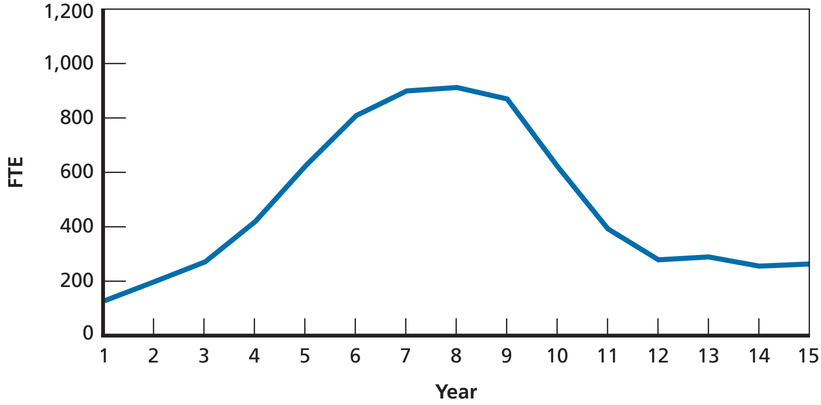
RAND *MG1033-3.3*

Figure 3.4
RAND Estimate of Number of FTE Draftsmen and Engineers Required by Industry to Design a Large, Conventional Submarine, by Year (15-Year, 8-MMH Design Effort)



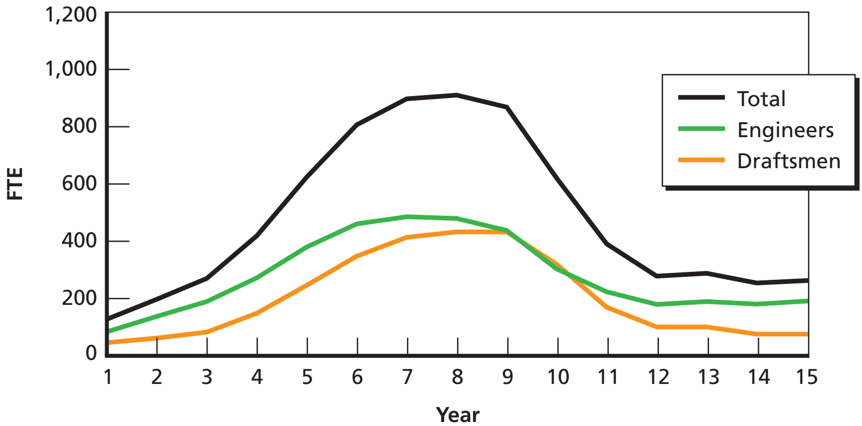
RAND *MG1033-3.4*

Figure 3.5
RAND Estimate of Number of FTE Personnel Required by Industry to Design a Large, Conventional Submarine, by Year (15-Year, 12-MMH Design Effort)



RAND *MG1033-3.5*

Figure 3.6
RAND Estimate of Number of FTE Draftsmen and Engineers Required by Industry to Design a Large, Conventional Submarine, by Year (15-Year, 12-MMH Design Effort)



RAND *MG1033-3.6*

be able to maintain the schedule. The downward slope of the curves shows tailing off of demand for the lead ship design and construction support effort.[5] However, the downward slope does not show the continuing demand for design skills to

- provide construction support for the 11 follow-on vessels in the class
- provide design upgrades to the class, including design support for the construction of later ships
- support sustainment of delivered Future Submarine vessels.

These figures are followed by three tables. Table 3.3 shows the total and maximum annual number of FTE personnel required for the 8 MMH and 12 MMH levels of effort, broken down by skill level. Tables 3.4 and 3.5 show our estimates of the number of each skill (measured in FTE) that would be required each year for 8 MMH and 12 MMH levels of effort, over 15 years.

As we noted earlier in this chapter, the data underlying these figures and tables are an analytical construct. Their purpose is to establish ROM levels of demand that RAND will use in subsequent analyses to determine the degree to which Australia's domestic design capabilities can meet the Future Submarine's anticipated design workload. *We caution readers not to be misled by any precision that the numbers imply. Many internal and external factors can and will impact the range of man-hours.*

[5] During construction of the lead (and follow) ship, design organisation skills are needed to answer inquiries from the building shipyard, correct design errors, and resolve nonconformance issues from the building shipyard and equipment suppliers.

Table 3.3
RAND Estimate of the Number of FTE Personnel Required by Industry to Design a Large, Conventional Submarine, by Competency

		RAND Estimate 8 MMH		RAND Estimate 12 MMH	
	Skill Competency	**Total FTE (% of total)**	**Maximum Annual FTE**	**Total FTE (% of total)**	**Maximum Annual FTE**
Draftsmen	Electrical	428 (10)	64	643 (10)	96
	Mechanical	266 (6)	39	397 (6)	58
	Piping/HVAC	350 (8)	58	521 (8)	86
	Structural/arrangements	667 (16)	89	999 (16)	134
	Other	316 (7)	39	473 (7)	58
Engineers	Signature analysis	160 (4)	20	237 (4)	29
	Combat systems and ship control	559 (13)	51	837 (13)	77
	Electrical	298 (7)	39	443 (7)	58
	Fluids	184 (4)	26	273 (4)	39
	Mechanical	187 (4)	26	277 (4)	39
	Naval architecture	521 (12)	64	779 (12)	96
	Planning and production	96 (2)	13	142 (2)	20
	Structural/ arrangements[a]	—	—	—	—
	Testing	76 (2)	7	108 (2)	10
	Management	144 (3)	13	216 (3)	20
	Engineering support	219 (5)	26	327 (5)	39
	Other engineering	361 (8)	39	536 (8)	58
Total		4,832 (100)	613	7,208 (100)	917

[a] Grouped with naval architecture.

Table 3.4
RAND Estimate of Number of FTE Personnel Required by Industry to Design a Large, Conventional Submarine, by Competency and Year, 8 MMH

	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Electrical design	4	8	11	13	32	51	64	64	64	51	26	13	13	7	7
Mechanical design	4	6	8	13	21	26	39	39	39	26	13	8	8	8	8
Piping vent design	4	7	7	13	21	26	45	58	58	45	26	12	12	8	8
Structural design	11	13	20	39	64	89	89	89	89	64	34	20	20	13	13
Other design	7	7	9	20	26	39	39	39	39	26	13	13	13	13	13
Electrical	7	9	13	20	26	39	39	39	39	26	13	7	7	7	7
Mechanical	6	7	7	13	20	26	26	26	20	13	7	4	4	4	4
Fluids	3	7	7	13	20	26	26	26	20	13	7	4	4	4	4
Naval architecture/structure and arrangements	11	20	26	39	51	64	64	64	51	39	26	20	20	13	13
Combat systems	11	20	26	39	51	51	51	51	51	39	39	39	39	26	26
Signature analysis	4	4	7	9	13	16	20	16	13	11	7	7	7	13	13
Planning/production	2	3	4	4	7	13	13	13	13	7	4	4	3	3	3
Testing	2	3	4	4	7	7	7	7	7	4	3	3	4	7	7
Management	4	7	11	13	13	13	13	13	13	11	11	7	7	4	4
Engineering support	4	7	11	13	26	26	26	26	26	13	13	7	7	7	7
Other engineering	4	7	11	13	20	26	39	39	39	26	20	20	26	32	39
Total	88	135	182	278	418	538	600	609	581	414	262	188	194	169	176
Draftsmen	30	41	55	98	164	231	276	289	289	212	112	66	66	49	49
Engineers	58	94	127	180	254	307	324	320	292	202	150	122	128	120	127

Draftsmen   Engineers

Table 3.5
RAND Estimate of Number of FTE Personnel Required by Industry to Design a Large, Conventional Submarine, by Competency and Year, 12 MMH

	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Electrical design	6	12	16	20	48	77	96	96	96	77	39	20	20	10	10
Mechanical design	6	8	12	20	31	39	58	58	58	39	20	12	12	12	12
Piping vent design	6	10	10	20	31	39	67	86	86	67	39	18	18	12	12
Structural design	16	20	29	58	96	134	134	134	134	96	50	29	29	20	20
Other design	10	10	14	29	39	58	58	58	58	39	20	20	20	20	20
Electrical	10	14	20	29	39	58	58	58	58	39	20	10	10	10	10
Mechanical	8	10	10	20	29	39	39	39	29	20	10	6	6	6	6
Fluids	4	10	10	20	29	39	39	39	29	20	10	6	6	6	6
Naval architecture/structure and arrangements	16	29	39	58	77	96	96	96	77	58	39	29	29	20	20
Combat systems	16	29	39	58	77	77	77	77	77	58	58	58	58	39	39
Signature analysis	6	6	10	14	20	23	29	23	20	16	10	10	10	20	20
Planning/production	2	4	6	6	10	20	20	20	20	10	6	6	4	4	4
Testing	2	4	6	6	10	10	10	10	10	6	4	4	6	10	10
Management	6	10	16	20	20	20	20	20	20	16	16	10	10	6	6
Engineering support	6	10	16	20	39	39	39	39	39	20	20	10	10	10	10
Other engineering	6	10	16	20	29	39	58	58	58	39	29	29	39	48	58
Total	126	196	269	418	624	807	898	911	869	620	390	277	287	253	263
Draftsmen	44	60	81	147	245	347	413	432	432	318	168	99	99	74	74
Engineers	82	136	188	271	379	460	485	479	437	302	222	178	188	179	189

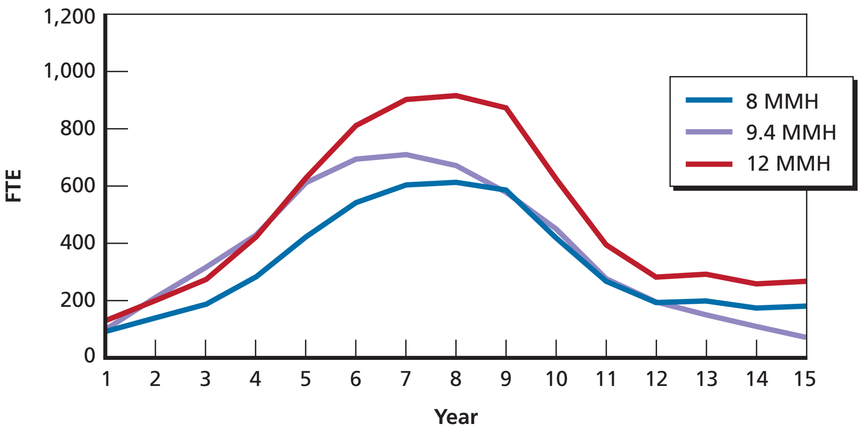
Draftsmen　Engineers

Predictions of Future Demand: Summary

Many decisions yet to be made will affect the level of effort and precise skills required to complete the Future Submarine design. We estimate that the total level of effort for the platform contractor will be between 8 MMH and 12 MMH and will require a variety of skills and experience. Figure 3.7 displays the level of effort that we estimate will be required to design the Future Submarine. It also displays the 9.4-MMH point prediction provided by submarine design experts with whom we consulted.

As Figure 3.7 shows, the upper range (12 MMH) will involve a steeper growth rate, a higher peak, and a more rapid rate of decline in the design force than the lower levels. At the peak, between the eighth

Figure 3.7
Predicted Personnel Required to Design the Future Submarine (8 MMH, 9.4 MMH, and 12 MMH Levels of Effort)



RAND *MG1033-3.7*

and ninth years, the figure suggests that between 600 and 900 design personnel will be needed for the design effort. At the end of the design effort, the involvement of fewer than 300 personnel will be required.[6]

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6 In the United States, draftsmen are entry-level designers.

CHAPTER FOUR

Government Demand: Estimates of Manpower Required to Oversee and Manage the Design of the Future Submarine

The Government, through DMO, has ultimate responsibility for a safe, effective, and affordable submarine design. In order to ensure such a design, the Government is responsible for setting requirements and ensuring that the design efficiently meets those requirements. It can do so by exercising technical authority, establishing safety criteria and performing a thorough testing programme, engaging in programme management and oversight, and maintaining capabilities not supported by industry (such as specialised component design or R&D programmes). Fundamentally, the Government chooses the role it plays in the design process, and that choice determines the resources required.[1]

This chapter first describes the roles and responsibilities that the Government could play in supporting a domestic submarine design. We then provide estimates of the Government's level of effort. The estimates are based on the limited historical data describing previous submarine designs; they reflect a range of required resources corresponding to either more or less intensive Government participation in the design process.

[1] Some choices will require rethinking and perhaps radical changes if a more active Government role in the design process is desired.

Our discussion of government roles and responsibilities is informed by our previous work on submarine design[2] and through interviews with Government officials about the *Collins* experience and plans for the future submarine. Historical data on the U.S. and UK submarine design experience provide estimates for the required government personnel as a percentage of the required industry personnel. The U.S. and UK experiences correspond to more and less intensive Government participation in the design process and thus allow us to estimate the range of required Government personnel based on the industry estimates derived in Chapter Four. Assumptions required for these estimates are described in more detail below.

Government Roles and Responsibilities

A primary consideration in the next design effort will be the respective roles and responsibilities of industry and Government. Even given assistance from allies, many decisions that will affect personnel resource and facility requirements remain. Specific areas in which Australia will need to develop an organic capability will become clearer as negotiations on intellectual property and other agreements between countries and corporations proceed.

First, the Government is responsible for requirements development and ensuring that the design efficiently meets those require-

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[2] See, for example, John Birkler, John F. Schank, Giles K. Smith, Fred Timson, James Chiesa, Marc Goldberg, Michael Mattock, and Malcolm MacKinnon, *The U.S. Submarine Production Base: An Analysis of Cost, Schedule, and Risk for Selected Force Structures*, Santa Monica, Calif.: RAND Corporation, MR-456-OSD, 1994; and John F. Schank, Mark V. Arena, Paul DeLuca, Jessie Riposo, Kimberly Curry Hall, Todd Weeks, and James Chiesa, *Sustaining U.S. Nuclear Submarine Design Capabilities*, Santa Monica, Calif.: RAND Corporation, MG-608-NAVY, 2007.

ments. Government's technical authority includes establishing safety criteria, determining a testing programme to verify performance, and participating in the management and oversight of the design. The Government should have final technical adjudication as to whether design elements adhere to established technical standards and policy. This technical adjudication must look not only at individual elements of the design but also at the interaction of individual elements as they aggregate to larger systems and structures. To be effective, the technical adjudication must be independent of programme management to ensure that technical standards are upheld in the face of project schedule or cost-savings demands. As the end user of the submarine design, the Government and RAN must ensure that the design efficiently meets the programme requirements. Either DMO can get heavily involved in the design process, effectively designing the submarine itself, or it can undertake periodic detailed and painstaking reviews of the physical mock-up and the development of design products.

Second, the Government must establish the extent of the submarine safety criteria, following or expanding the submarine safety and hull integrity model used for the *Collins*.[3] Safety may be limited to preventing and recovering from flooding, or it may be more extensive and address the gamut of safety-related issues, such as depth excursions, control system failures, fires, atmosphere contaminates, and high-temperature/pressure fluid systems. If the Government does not wish to maintain the required technical acumen, does not possess requisite past experience, or does not desire to develop design rules and process documents related to safety criteria, it can turn to independent third parties that can produce pre-packaged ship design and construction rules. The design authority should initiate development of the submarine safety criteria and oversee its execution.

[3] Sometimes referred to as SUBSAFE.

Third, the Government may also re-establish the testing programme put in place during construction of the *Collins* class. A testing programme not only ensures that a submarine meets requirements, it also provides important feedback to the design process and allows changes to be made for subsequent ships built using the same design. The design authority should initiate the development of such a testing programme and oversee its execution.

Finally, the Government may be responsible for maintaining or developing the technology base that the RAN requires or will require. This includes R&D activities that are not performed by industry but that are germane to current and future submarine capabilities. There may be submarine components of such a nature that the Government retains responsibility for their development.[4] This includes designing and developing components for which there is insufficient demand to sustain an industrial base but that are critical to the submarine or that are required for the integration and interoperability of certain systems.[5] Additionally, the Government might have to maintain testing facilities that are required in the submarine design process but are not commercially viable for private industry.

Estimating the Demand for Government Personnel

Required Competencies

The competencies the Government requires will depend upon the chosen role of the Government in the submarine design process and

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4 For example, the U.S. Navy designed the *Virginia*-class propulsor and supplies it to the shipyard as government-furnished equipment.

5 In the United States, this includes integration and interoperability of the C4I and combat control systems.

the amount of participation they desire in the platform contractor/design agent and sub-contractor design teams. However, we assume that the Government will maintain some level of technical authority and expertise in order to act as a "smart buyer", whether it employs a design authority to assist it or not. Table 4.1 summarises the types of technical and programme management skills that should reside within the Government so that it maintains its ability to exercise technical authority. It is evident from this list that the Government must broadly maintain the same breadth (but not the depth) of technical skills that industry possesses, in addition to the programme management and oversight skills.

Table 4.1
Government Competencies Required to Oversee Submarine Programmes

Technical Skills	Programme Management
Requirements development	Contracting
Naval architecture	Finance
Mechanical engineering	General and programme management
Electrical engineering	Planning and production oversight
Structural engineering	Test and commissioning
Arrangements engineering	Design management
Signature analysis	Cost estimation
Fluids	Government and regulatory body liaison
Systems engineering	Risk management
HVAC	
Combat and ship control systems	
Safety and operability	
Habitability	

In addition to the above competencies, the Government capability should also include Navy personnel who can bring the operational perspective to the design team.

Historical Level of Effort

A detailed analysis of the factors affecting the level of Government participation in the Future Submarine programme is beyond the scope of this research.[6] However, we can derive upper and lower bounds on the total Government-level effort by assuming that, for a fixed Government role, the total Government level of effort on a given design is proportional to the total industry level of effort for the same design. This assumption is reasonable because the Government work profiles depend on the same factors that determine industry work profile (technical risk, size, and complexity of the submarine, and magnitude of design detail; see Chapter Three). This is in addition to the design role the Government chooses to assume and the extent to which it fulfils that goal directly or indirectly.

Our analysis of the *Upholder* and *Collins* program data suggests that the government will need a technical workforce dedicated to supporting a submarine design that is approximately 15–22 percent the size of the platform contractor workforce.[7]

Chapter Three provided estimates of the total industry level of effort for potential Future Submarine designs. At the lower estimate of design efforts, 8 MMH, this translates to a Government demand of

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[6] See Schank et al., 2007.

[7] The low estimate is based on the proportion of Government employees to platform contractor employees derived from UK submarine design experience and assuming little component design. The high estimate is based on the proportion of Government employees to platform contractor employees derived from U.S. submarine design experience and assumes significant component design.

about 80 dedicated personnel. At the upper estimate, 12 MMH, this translates to a Government demand of about 175 dedicated personnel.

The distribution of Government work over time tends to be relatively constant in comparison to the industry profile (that is, its profile is "flatter"). In all cases, industry's design effort is characterised by a buildup in effort during conceptual and detailed design, followed by a decreasing effort as the design is completed and construction begins. At the initiation of a new submarine design, the Government must articulate specifications that determine design parameters for industry. During the height of detailed design, Government must support the large industry design effort. This support includes active participation in the design process as well as approval of final design products. Finally, as industry transitions from detailed design to construction, the Government has a substantial and ongoing test and evaluation responsibility. As a result, the profile for the Government level of effort tends to be relatively flat through the entire process.

The location of these Government-based technical and programme management individuals within the DMO, the RAN, the Defence Science and Technology Organisation (DSTO), and the platform contractor's site will require careful consideration.

Who Can Perform the Government Role?

Particularly challenging is making sure that the programme adheres to established technical, operational, and safety requirements. If the Government is to perform this function directly, significant technical resources and expertise would be needed. Hiring large numbers of Government employees to perform these duties may commit the Government to long-term employments that may not be in its best interest. Alternatively, the Government could hire a smaller number of Government engineers and an independent and objective design authority to perform this function on its behalf. A team composed of a cadre of Government engineers and the design authority contractor would perform the function of technical authority. The design authority would be organisationally separate and independent of the platform contractor/design agent (those actually responsible for executing the design, including the major system procurements and developing the construction work packages). However, Government engineers, the design authority, and the design agent should work hand-in-hand, with the common object of ensuring programme success. In either case, the Government retains the ultimate authority for cost, schedule, and capabilities (and assumes the associated risk).

The evolution towards privatisation of various technical and managerial functions within the shipbuilding industry has occurred in many countries, including the United States, the UK, and Australia. In some instances, the decision to divest government expertise resulted in unacceptable outcomes, such as significant cost and schedule growth or inadequate development of desired capabilities.[8] These unacceptable outcomes and increasing concern over the appropriate role and level of government involvement in defence acquisition prompted a study of this issue. A RAND report on the UK MoD's roles and required technical resources for the UK submarine industrial base argued that best commercial practices support a "partnership" model, whereby government and industry are partners throughout the acquisition process.[9] This research suggests that the Government should maintain certain functions that are required to manage the technical and other programme risks and act as a "smart buyer". These functions include pro-

[8] See Schank et al., 2005.

[9] In this model, each partner takes a leading or following role, depending upon the acquisition phase. This research suggests that the Government should have the capability to lead the requirements generation, to be a leading partner with industry on the concept development, and to be a following partner on the detail design of the boat. See Schank et al., 2005.

gramme management, technical oversight/authority, and support of research and development.

Government Demand for Design Skills: Conclusion

In this chapter, we described the government's roles in the submarine process. Government is responsible for developing requirements and ensuring that the design efficiently meets those requirements. It does this by exercising technical authority; establishing safety criteria and performing a thorough testing programme; engaging in programme management and oversight; and maintaining capabilities not supported by industry, such as specialised component design or R&D programmes.

Based on limited historical data on U.S. and UK submarine design experience, we estimate the total Government level of effort to be 15 percent to 20 percent of the total industry level of effort, depending largely on the level of involvement the Government chooses to have in the design. This translates to a dedicated Government effort of 80 to 175 personnel.

CHAPTER FIVE

Facilities and Tools Required to Design a Modern Submarine

The engineering facilities and software tools required for a submarine design depend on a variety of factors. These factors include the complexity of the submarine, the amount of design recycling from the previous generation of submarines, and the government's acceptance of risk—both technical and operational. These choices, not as yet made in the case of the Future Submarine, affect which facilities and tools are required. There are examples of modern submarines designed without access to sophisticated software design tools,[1] as well as examples that reveal the utility of these tools.[2]

In this chapter, we briefly discuss our analysis of tools for submarine design. We considered the design areas judged to be critical, sophisticated tools for those design areas, less-sophisticated alternative tools, and the risks associated with the use of less-sophisticated alterna-

1 Two successful American submarine designs, the USS *Albacore* (AGS-569) and the *Los Angeles* (SSN-688) class, were completed without the use of such tools.

2 It is frequently claimed, for example, that the USS *Seawolf* (SSN-21) is quieter at 25 knots than previous-generation *Los Angeles*–class submarines tied up alongside a pier. The detailed design process for the *Seawolf* depended heavily on sophisticated design tools, including computer software (such as simulation models), equipment (such as test vehicles or measuring devices) and facilities (such as tow tanks) and large-scale models/vehicles.

tive tools. Detailed material supporting the findings of this chapter is provided in Appendix D.

Facilities and Software Tools

Three categories of sophisticated modern design tools emerged in our analysis:

- Category 1: Tools that must be developed domestically. If absent, they carry substantial risk to the design.
- Category 2: Tools that need not be developed. If absent, they carry moderate risk to the design.
- Category 3: Tools that can be substituted with little or no attendant risk.

Looking ahead to our gap analysis, Category 1 tools represent the greatest potential problems; their development can require a long lead time, whereas tools that can be acquired or provided commercially require less lead time. Category 2 tools need not be developed domestically but rather can be purchased under license or used under contract. Current gaps in Category 2 and Category 3 tools are relatively unimportant; sophisticated tools in those categories can be acquired relatively quickly, can be replaced by less-sophisticated tools with little risk, or are not needed.

Category 1, 2, and 3 Tools

Tables 5.1–5.3 display results for the three categories by design area. The tables briefly describe each design area judged critical and the risks

Table 5.1
Category 1 Risks

Design Area	Design Area Description	Risks Associated with Design Area
Hydrodynamics	Treats flow over the entire exterior of the submarine (both hull and appendages)	Increased drag, hard-to-diagnose flow-induced radiated noise Own-sensor performance degradation Note: Risks can be reduced for given designs using scale models
Acoustic analysis	Addresses the total radiated noise signature of submarine designs Radiated noise that an enemy might detect Self-noise that that would degrade performance of the design submarine's sonar sensors Sources of the acoustic energy onboard the submarine Mathematical transfer functions that characterise how this energy gets into the water or other onboard structures and systems	Increased detectability Degraded own-ship sonar performance Difficulty and expense in identifying and correcting structure-borne, fluid-borne, or air-borne noise
Structural acoustic analysis	Design and analysis of ship systems for the purpose of understanding and mitigating radiated noise levels Design and analysis of structures; components; and noise mitigation devices, arrangements, features and treatments Analysis and mitigation of noise resulting from propeller-induced forces in the submarine that radiate in the far field	Increased detectability Additional structure weight at the expense of payload Difficulty and expense in correcting radiated noise Note: System of systems techniques are recommended here; e.g., engine mounts that reduce transmitted vibration may also allow excessive engine movement, increase pipe stresses, or increase susceptibility to shock

Table 5.1—Continued

Design Area	Design Area Description	Risks Associated with Design Area
Sonar engineering	Design, selection, and layout of sonars and supporting structures	Inadequate sonar detection ranges or gaps in sonar coverage Tactical advantage in encounters with adversary submarines may be reduced or lost Greater burden placed on (possibly expensive) radiated noise technologies

Table 5.2
Category 2 Risks

Design Area	Design Area Description	Risks Associated with Design Area
Submarine arrangements	Layout and integration of the pipes, valves, pumps, motors, electrical wiring, switchboards, batteries, structures, and foundations	Greater likelihood of design errors Greater expense in correcting design errors
Applied mechanics	Design and analysis of submarine structures and components for all static, dynamic, and vibration-induced loading conditions Prediction of transient response to underwater explosions	Additional weight at the expense of payload
Shock qualification	Analysis of response to close onboard underwater explosions	Simple "G" acceleration models can lead to significant additional weight at the expense of payload Note: Shock qualification test facilities can be used to reduce risks for given designs

Table 5.2—Continued

Design Area	Design Area Description	Risks Associated with Design Area
Structural analysis	Analysis of response of internal and external structures to operational and shock loading	Unacceptable deformation (buckling) analysis requires more sophisticated tools Loss of submarine and all crew members
Fluid dynamics	Results of internal (e.g., piping) and external (e.g., control surface) flows	Semi-empirical tools can be used with little risk or weight penalty
Pipe stress analysis	Addresses static and dynamic loading resulting from the effects of gravity, submarine movement, temperature changes, internal and external pressure changes, and changes in fluid flow rates	Pipe failures with flooding, or loss of cooling, or hydraulic systems Imposition of operating depth restrictions Note: In all cases metallurgical data are essential to limit risks
Propulsion system analysis	Hydrodynamic design and model testing; speed/powering and fuel endurance analysis Equipment sizing, selection, procurement, and evaluation Mechanical and electric drive system design Propulsion system trade-off studies to balance performance and cost Shaft sizing, arrangement, and alignment studies Reliability, maintainability, and availability analyses and failure mode, effects and criticality analyses Equipment and hull girder vibration analysis	Various, including performance, efficiency, reliability, noise, additional weight (at the expense of payload), and safety Note: Overlaps with other design areas (e.g., applied mechanics, structural analysis), encouraging a common tool kit Land-based test facilities can be used to reduce risks for given designs

Table 5.2—Continued

Design Area	Design Area Description	Risks Associated with Design Area
	Airborne and structure-borne noise predictions (for radiated and self-noise) Shock qualification Intake/uptake testing/analysis Dynamic response analysis Controls system engineering Total ownership cost analysis; land-based test facility design	
Hydro-acoustic analysis	Predict and control flow-induced noise and vibration Vibration sources and analysis of structural response to and radiation resulting from these forcing functions Noise resulting from flow over the hull and especially noise generated by structural interaction of the propellers and structural interactions caused by the propeller	Noise and unexpected flow anomalies may be discovered during initial sea trials or during subsequent operations that will have to be isolated and corrected

Table 5.3
Category 3 Risks

Design Area	Design Area Description	Risks Associated with Design Area
Naval architecture	Point design development including arrangements, displacement, weights, hull form, speed, payloads, signatures, and cost	Manual design work limits the number and quality of concepts that can be evaluated Innovative concepts may not be evaluated

Table 5.3—Continued

Design Area	Design Area Description	Risks Associated with Design Area
Fluid systems	Design of plumbing, hydraulics, drains, compressed air systems, and seawater and freshwater cooling systems	Relatively simple tools may not support acoustic or heat flow analysis of fluid systems Risk can be mitigated using test loops
Mechanical systems and components	Design of weapons handling and launch systems, retractable masts, steering and diving systems, ship hatches and doors, winches, etc.	None—designs do not require sophisticated design tools
Software development	Design of software for ship automation and monitoring	None—risks are in process, not tools
Electrical analysis	Design of main generators, battery systems, main switchgear and power distribution equipment, system protection equipment, and electrical system control and monitoring	None—risks are in process, not tools
Radar analysis	Radar analysis for diesel-electric submarines primarily addresses radar cross section of masts (periscopes, antennas and the snorkel)	None—numerous good radar cross-section models are available for iterative design efforts
Systems engineering	Technically develops, integrates, and optimises all systems in the ship and prepares technical deliverables	None—normally conducted using small specialised computer models
Design management	Formalise the tasking and scheduling relationships associated with designing, building, and testing a submarine	None—risks are in process, not tools

associated with not using appropriate tools in that area. We recognise that design areas can overlap. For example, shock qualification (which considers the response of the submarine design to explosions) and structural analysis (which considers internal and external structures and components for operational and shock loading) clearly overlap. We ignore such overlaps for clarity.

Systems Engineering and Design Management Tools

The need for systems engineering and design management tools is not always recognised in discussions of submarine design processes. In the context of submarine design, systems engineering technically develops, integrates, and optimises all systems in the ship and prepares technical deliverables by

- developing and evaluating system concepts and new components, conducting trade-off studies, developing system diagrams, class drawings, component specifications, etc.
- performing safety analyses on new and significantly modified legacy ship systems and components.
- Design management tools are used, for example, to define major ship modules; the sequence in which components are procured; the integration of deck structures; and the building, installation, and testing of major sections of the ship (i.e., a manufacturing and assembly plan [MAP]). Design management tools and technical performance measures also importantly facilitate management of growth and margin during the iterative process of submarine design; design changes in one area can ripple into other areas, causing growth or reduction of margins (such as plant capacities and reserve buoyancy). The management of growth and margins

must be rigorous to maintain design integrity. Much of growth and margin management deals with data and with tracking collective trends as designs evolve.

CHAPTER SIX

Measuring Supply: Survey Overview

We now turn to the question of what submarine design resources currently exist within Australia. Here, RAND pursued a two-pronged research approach. We sent a survey instrument to 56 industry, Government, and academic organisations requesting various types of data and information. Following an initial analysis of the survey responses, we conducted on-site interviews to clarify the responses to the survey questions and to better understand the submarine-design capabilities of the various organisations.

The survey covered a broad range of topics intended to solicit information in three primary capability domains:

1. *General information*—questions on the submarine products and services provided, specific areas of expertise that might be applicable to submarines, the level of corporate experience in the business of submarines, and commercial viability
2. *Workforce information*—questions on
   - current workforce status, including the design and engineering skills applicable to submarines and the level of individuals' experience in working on submarine programmes

- the ability to grow the workforce, including hiring practices and experience, average attrition, time to gain proficiency, and the available pool of new recruits
- future workload demands, including expected future design work

3. *Design tools and facilities*—questions on the design tools in use, the phase of design in which each tool is employed, the capability of the tools, their level of customisation, experience with physical and electronic mockups, and the types of facilities available for submarine design and testing.

The workforce information addressed a primary group of skills that were selected to cover the broad range of technical expertise required to design a submarine. The survey, reproduced in Appendix A, provided a list of the skills and a brief description of the skill categories.

We sent the survey to 46 companies, seven Government entities, and three universities. These organisations were identified as having some potential capability for the Future Submarine programme.

Treatment of Missing Data

The responses we received represent the vast majority of the submarine-design capability in Australia and are the basis of our reported statistics. An evaluation of the firms that did not respond to the survey was conducted through publicly available information and direct contact with those companies. From this evaluation and an evaluation of the DMO database on defence-related industrial capabilities and other commercial databases, we estimate that the response constitutes at least 95 percent of the submarine-design capability in-country.

Many of the survey responses were missing key information, such as the average number of employees; their age, experience, and skill; the average number of annual recruits and attrition; revenue and rate data; the number of years required for a new hire to become productive; hiring sources for new draftsmen and engineers; and the experience level of new hires.

In some cases, we replaced missing data with proxy data. For example, we used estimates of current revenue and expected growth as a proxy for future workload demands. When information on workforce experience was not provided, we used the distribution of revenues amongst submarine and other work as an indication of the presence or absence of submarine experience.

Although several firms identified their ability to access applicable resources from their overseas counterparts (which we refer to as reach-back), we included only the indigenous capabilities in our initial evaluations. Reach-back capabilities will be explored when we evaluate options to close the gap between the demand for resources for a new submarine design and the availability of those resources in Australia.

Organisation of Industry Survey Responses

We created a taxonomy to help us organise and assess submarine-design capabilities in industry. The taxonomy consists of five major groups of submarine-design resources. Table 6.1 provides a general description of each group. In our study, we assigned each company to one of those groups.

The companies designated as platform-design companies are those that offer platform-level design and integration services and that have experience designing ships and or submarines. These companies may also construct platforms and offer in-service support services. There were four respondents that provided platform-design capabilities, three of which have had experience with submarines. Some of the specific capabilities identified include

- design, construction, and in-service support of submarines
- high-speed, aluminium, surface-ship design and construction
- ship design and construction, platform and mission-system integration, naval platform and systems through life support, naval weapons-system modelling, design, development, manufacture and support, and naval repair and maintenance
- submarine concept–formulation activities and studies.

The eight organisations designated as technical-expertise companies offer analytical or other support services, such as consulting services, structural analyses, or support of specific equipment. In general, these companies do not provide detailed design plans but can support design activities. Some of the specific capabilities identified include

Table 6.1
Organisation Tier Structure and Definitions

Tier	Definition
Platform design	Companies that provide design, construction, integration, or in-service support at the platform level
Technical expertise	Companies that provide analytical support services or other technical services, such as design work
Combat system supplier	Companies that provide combat-system services or equipment
Component supplier	Companies that provide equipment components
Engineering procurement, construction management (EPCM)	Large companies that provide engineering and other services to the commercial market, especially to the oil, gas, and mining sectors

- design, substantiation, and certification services for aircraft modifications and repairs plus other in-service engineering support
- design and engineering consulting, advanced analysis in safety/risk engineering, naval engineering, technical regulation, and acquisition support
- design and engineering support of naval combatants
- cost analysis, capabilities modelling (including requirements analysis and capability definition), safety management, and engineering design
- aerospace engineering, including engineering services in aircraft structural design and analysis as well as installation design of systems in airframe and marine applications
- design for the integration of Caterpillar engines into submarine-specific power-generation packages and generator package design and support
- support of power-conversion equipment, propulsion control, search-and-attack periscopes (including development of sensors and the manufacture of periscopes), hull penetrators (including their manufacture), switchboards, generator rectifiers, launcher control systems (including their design and manufacture), dive and safety consoles, and weapons data converters
- engineering modelling and analysis of structural integrity and dynamics, piping systems, computational fluid dynamics, vibration and onboard acoustics, underwater acoustics, advanced rotor dynamics, machine vibration, and noise analysis
- analysis of acoustics, vibration, and corrosion.

Six combat-systems suppliers responded to our survey. Of those six, five provided useful information about combat systems, combat-system design, or integration products and services. Some of the specific systems and services provided include

- integrated platform-management systems; machinery control and monitoring; towed and hull arrays; sonar and processing systems; echo sounders (single and multi-beam); navigation systems; communications systems (underwater, internal, external); anti-submarine warfare and mine-warfare systems; underwater-measurement ranges and ocean science laboratories; multi-panel operator consoles; voice announcing systems; battle-damage systems; dynamic positioning and control systems; degaussing systems; high-shock-tolerant circuit breakers; switchboards and power panels; vessel simulators and training systems; command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) systems; main switchboards; composite fins; and hull components
- complex electronic systems and C4ISR
- combat systems design, construction, and in-service support
- design and manufacture of a sonar suite, signature management, and secure information systems network design and supply
- design, implementation, and integration of submarine Tactical Data System and Sensor Data Fusion architectures
- in-service support services for the design, installation, maintenance, repair, and long-term engineering sustainment of the *Collins*-class communications system for both internal and external communications.

Eight component suppliers responded to our survey. Seven of those eight provided useful information about component-design products and services. Some of the specific components and services they discussed include

- application of composites for submarine pressure vessels and other parts of the structure, such as casings, fin/sail structures, hatches, and doors
- discharge systems
- design and manufacture of a number of hydraulic and pneumatic system fittings
- design, manufacture, and in-service support of main storage battery cells, cell ancillary items (such as electronic monitoring and cooling hoses), battery cooling, and agitation skids
- development and support of submarine ship-control systems
- support for the Integrated Platform Management System (IPMS) and electrical and mechanical design capabilities
- design and construction of main switchboards.

Two large engineering, procurement, construction management (EPCM) firms (WorleyParsons and SKM) have significant numbers of technical resources but little or no experience in naval systems. Some of the specific services provided include

- engineering services for design, construction support, and in-service support to a broad range of complex process industries, including the offshore oil and gas and the resource-industry sectors
- engineering and project-management consulting, which provides the Department of Defence with technical capability in the areas of engineering, integrated logistics support, risk assessment, and programme management.

Survey Caveats

The results of our analyses are accompanied by three main caveats. First, the survey responses represent the firms' own assessments of their capabilities, not RAND's. Second, conclusions drawn from the surveys may not be representative of the total capabilities within Australia.[1] Approximately half of the organisations that were sent the survey did not respond, so we estimated their potential contributions. Finally, a number of those that did respond did not answer some critical questions. This precluded us from completely understanding the status of the submarine-design resources in Australia.

[1] We recognise that some firms may tend to inflate their capabilities when asked about them; as a result, a subset of responses to our survey might overstate certain capabilities. Nevertheless, our survey constitutes the only quantification of available skills across Australia.

CHAPTER SEVEN

Design Personnel, Facilities, and Software Tools Available in Australian Industry

The ability to design a submarine within budget and on schedule is a function of the availability of personnel with the required experience. Growing the required talent and developing the software and facilities used in the design process add cost and require time. This chapter identifies the personnel, software, and facilities available in Australian industry. To arrive at an assessment of the resources available for the Future Submarine programme, it also discusses the ability to grow personnel and assesses the future demand that may be placed on personnel.

Overall Technical Personnel Resource Levels and Submarine Experience

One of the top questions of this study is whether there are enough technical resources in industry to support a new submarine-design programme in Australia.[1] To begin to answer this question, one must understand the workforce that currently exists and its demographics and experience levels. Table 7.1 summarises the industry responses in terms of technical draftsmen and engineers for the five industry groups defined in Chapter Seven. Note that the two EPCM firms have the majority of the technical resources: Approximately 85 percent of the nearly 23,000 draftsmen and engineers shown in Table 7.1 are employed by them. Although this number would be more than sufficient to support a submarine-design programme, it is unclear whether all those people would be available in the time frame required and whether their skills are applicable to the Future Submarine programme.

An important observation from Table 7.1 is that there are very few draftsmen outside of the EPCM firms. For example, the ratio of draftsmen to engineers is 0.46, whereas this ratio for comparable firms in the United States and the UK ranges between 0.75 and 1.2. There-

Table 7.1
Technical Workforce, by Industry Group

Group	Draftsmen	Engineers
Platform	374	1,215
Technical expertise	66	260
Combat systems	55	1,205
Components	9	362
EPCM	6,695	12,713
Total	7,199	15,755

[1] Technical employees include the draftsmen, engineers, technical management, and technical support required to design a submarine.

fore, the data in Table 7.1 suggest that there may not be sufficient numbers of draftsmen to support a new design programme within the non-EPCM organisations, especially given the demands arising from other naval programmes.

A positive indication from the survey data is that, overall, the workforce has an average age of around 40. This suggests that many of those employed today should still be in the workforce in five to ten years. However, the downside of having a low average age is that many workers have a lower level of experience with naval and submarine products. An engineer with experience in the naval sector has an average of 12 years of such experience, and an engineer with experience with submarines has an average of less than five years of such experience. These averages suggest that the workforce has some experience with submarine design. We note that the firms reported that it takes an average of two to five years for a new hire to become fully productive. Some skills take even longer to acquire, sometimes up to ten years. Thus, the technical workforce may not be fully proficient with submarine design.

Company size amongst the industry groups varies widely, and there is a wide range of submarine experience. The two EPCM firms have many more employees than the other organisations, but their employees have either minimal or no submarine experience.

The technical-expertise firms are significantly smaller than those in the platform group, employing as few as six and no more than 150 technical personnel. This implies that these firms could be a source for augmentation of the design and engineering staff in specific domains, but they do not have the numbers of staff required for a full design effort. Although these firms do not have large numbers of people to apply to a design effort, they might employ specific analytical competencies of importance to the design effort.

The companies providing combat systems employ more than 1,250 total technical staff. These companies are medium to large firms, employing between 139 and 653 employees. Most of them also have large corporate offices in other countries. Component-supplier firms range from very small, employing only six personnel, to large, employing more than 1,100.

Another important question is how much submarine experience resides in the technical workforce. Table 7.2 shows the average years of submarine experience by industry group for draftsmen and engineers for those firms that provided the data. Notably, the combat system

Table 7.2
Average Years and Number of Draftsmen and Engineers with Submarine Experience, by Industry Group

Design Personnel, Facilities, and Software Tools Available in Australian Industry	Average Years of Submarine Experience[a]		Number with Submarine Experience	
	Draftsmen	Engineers	Draftsmen	Engineers
Platform	11.5	5.9	206	265
Technical	0	1.1	0	10
Combat systems	4	4.3	20	210
Components	2.0	2.3	2	13
EPCM	2.0	2.0	0	0

NOTES: Estimates of the number of individuals with submarine experience are based on the percentage of revenue from submarines and reported years of experience. They are inflated by 5 percent to adjust for non-response.

[a] Weighted averages.

and platform firm personnel have the highest average years of submarine experience, while the workforces of the components and technical firms have very little. This difference should not be terribly surprising because most of the technical work for the *Collins* programme focuses on the combat-system area. These results suggest that a new design programme will be more difficult in the area of components. Also, the data suggest that the platform firms may not be able to leverage much submarine experience at the technical firms.

Future Workforce Demands

The availability of the technical workforce to support the Future Submarine programme is problematic. Most of the combat-systems and platform firms are actively involved in the design of the Air Warfare Destroyer (AWD) and support of the *Collins* class. Although the design effort for the AWD should taper down, the programme will continue to need technical support from industry. Also, the offshore and mining sectors are very active right now. It is unclear whether any of the offshore or mining workforces will become available to work on a new submarine design.

Our estimates of the numbers of draftsmen and engineers suggest there are a large number of technical personnel working at the various industry organisations, although only a small percentage of those personnel have submarine experience. We assume that they are fully employed currently (i.e., that the companies are not carrying extra people on their personnel roles in anticipation of future work). A second question, then, is what the future demands for technical resources will be. If demand in the future declines, then personnel may be available to support the Future Submarine programme. However, if the various organisations are expecting an increase in revenues, they may have an increased demand for technical people. In the latter case, the Future Submarine programme may be competing with other programmes and projects for technical resources.

In the survey, we asked organisations to estimate the future demands for the various technical skills. Unfortunately, for a variety of reasons, few organisations provided future projections of demand. Without that information, it is difficult to estimate whether a portion of the current technical workforce may be available to work on the Future Submarine programme or whether the future demands placed on the various organisations will compete with the demands of the Future Submarine programme.

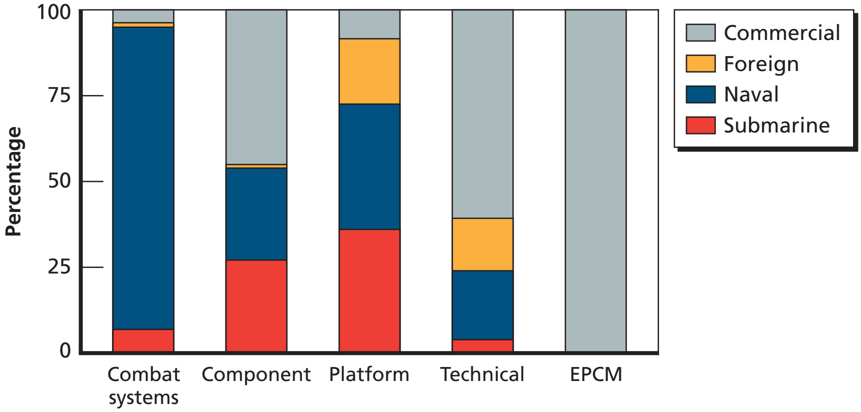
We used various other information from the survey responses to gauge the future demands for technical personnel. We first looked at the current and projected business base of the organisations, concentrating on the part of the business base that is dedicated to submarine work. We then looked at how the workforce levels of the organisations have changed over the last five years, seeking to understand whether they have experienced either growth or a contraction of their workforce. Finally, we compared the 2009 revenues the firms reported with their estimated 2010 revenues to understand whether they anticipate growth or contraction in the short term.

Sources of Revenue

Of the 29 companies, 20 indicated having some level of experience in designing, constructing, or supporting submarines. In some cases, this experience is extensive: Nine companies reported at least 20 years of experience in submarine design. Although many firms reported having many years of experience with submarine work, only 12 have actually sustained any submarine work based on reported revenues.

Figure 7.1 shows the percentage of fiscal year 2009 revenue by group, split into four areas: commercial and other work, foreign, Aus-

Figure 7.1
Source of 2009 Revenue for Each Group, FY 2009



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tralian naval work (other than submarines), and Australian submarine work. Not surprisingly, the EPCM firms were exclusively focused on commercial work. The revenue for the technical sector largely came from the commercial or non-naval sectors. Very little revenue resulted from Australian submarine work. The platform sector had the most revenue from submarine work—nearly 40 percent. About one-quarter of the component suppliers' revenue came from submarine-related work. The combat-system sector earned less than 10 percent of its revenue from submarine-related work, a substantial portion of which is not for design work but for product delivery and testing.

Current Submarine Workforce

Another related and important question is what percentage of the workforce was actively involved in submarine design in 2009. Table 7.3 presents this information by group. Note that very little of the workforce was actively involved in submarine-design work.

How the firms project revenue to change in the next five years should suggest how much activity will need to take place in terms of hiring and training new workers. It should also suggest whether any staff can move between sectors if there are surpluses. Table 7.4 summarises the percentage growth that the firms are anticipat-

Table 7.3
Percentage of Staff Active in Submarine Design in 2009, by Industry Group

Group	Percentage of Staff
Platform	18.9
Technical	0.5
Combat systems	11.0
Components	1.3
EPCM	0.0

Table 7.4
Number of Firms Anticipating Revenue Growth over the Next Five Years

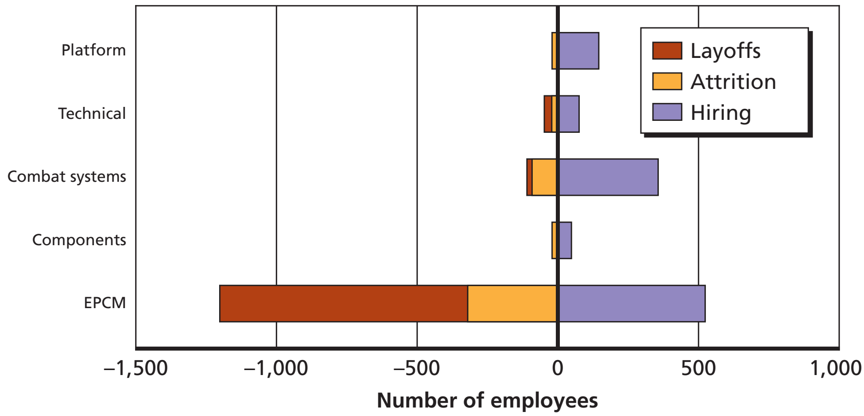
Group	0–50%	51–100%	>100%
Platform	1	1	1
Technical	2	4	1
Combat systems	2	3	1
Components	4	1	1
EPCM	0	1	0

ing. Note that firms did not report growth levels over 100 percent-but merely as greater than 100 percent. Although the combat-system providers anticipate moderate growth (on average), the other sectors expect healthy growth. Regardless of whether these revenue projections include the Future Submarine programme, these revenue projections suggest that hiring technical workforce over the next five years will be challenging.

Previous Workforce Changes

We asked the various organisations to describe how their workforce had changed in the previous five years: Did it grow or contract? Figure 7.2 shows the annual average change in the engineering workforce for the majority of the organisations. (There has been very little change in the draftsman workforce.)

Figure 7.2
Average Annual Change in Engineering Workforce Levels, 2005–2009



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The EPCMs have experienced an overall reduction in their engineering workforce over the past five years, but the other firms have experienced growth, especially the combat-system firms. If this growth continues, as Table 7.5 suggests it will, the Future Submarine programme may face a challenge in recruiting technical personnel to assist in the design of the new submarine.

Estimated Change in Revenues, 2009–2010

One additional measure of how the firms view the future demand for technical resources is their expectations for revenues in 2010 compared with their revenues in 2009. Table 7.5 shows the distribution of revenue growth (or decline) for the 21 firms that provided responses to survey questions about 2009 revenue and estimated 2010 revenue. Table 7.4 presented a longer-term view of the next five years, but Table 7.5 shows the short-term view of the coming year.

Almost all of the firms that provided information expect their revenues to grow in 2010 compared with 2009. Some of the anticipated growth is due to the new surface-ship programmes in Australia. Some is due to the introduction of the Joint Strike Fighter or to expansion

Table 7.5
Number of Firms Anticipating Revenue Growth or Decline from 2009 to 2010

Group	<0%	0–20%	21–40%	>40%
Platform	0	1	1	2
Technical	1	5	1	1
Combat systems	2	1	2	1
Components	1	2	1	1
EPCM	0	1	0	0

in the offshore and mining industries. Regardless of the source, this growth should result in a demand for additional technical personnel. This will present a challenge to the personnel demands of the Future Submarine programme.

Ability to Expand the Workforce

In the survey, we asked a number of questions about the ability of the firms to expand their workforce. One activity critical to expanding the workforce is the ability to mentor less-experienced workers. We asked the firms what they thought were typical mentoring ratios (i.e., how many inexperienced workers a fully experienced worker can train and supervise). Most responded that the ratio depended on the skill level of the new hire and the complexity of the task involved. Overall, the average mentoring ratio was 3 new hires to 1 experienced worker, a ratio that applied both to engineers and to draftsmen. However, the range varied from 1:1 to 6:1.

Another indicator of growth is the maximum growth rate that can be productively sustained. The responses about the maximum annual growth rate were quite varied, ranging from 15 percent to 100 percent. On average, the maximum sustained annual growth rate was 27 percent. Table 7.6 shows the maximum average growth rate by group.

A final indicator of the ability to expand the workforce is the source of new hires. The vast majority (87 percent) of new hires comefrom either universities or industry. Of these new hires, twice as many come from industry as from universities, indicating that the firms rely on getting skilled workers from other industries. This strategy works if the demands on the various industries are counter-cyclical. However,

Table 7.6
Maximum Average Annual Growth Rate, by Group

Group	Growth Rate (%)
Platform	34
Technical	36
Combat systems	20
Components	18
EPCM	25

if other industries are also active during the Future Submarine programme, these firms may find themselves either competing for workers (and having to pay more) or having to hire workers with less experience than they have in the past. Table 7.7 shows the percentage of new hires from universities and industry for each group.

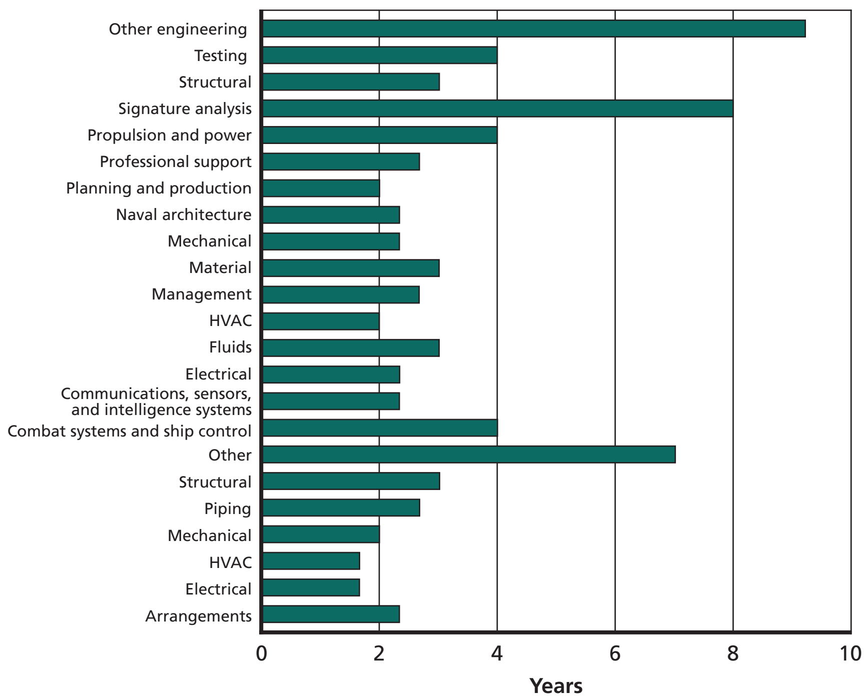
Table 7.7
Source of New Hires, by Group

Group	University (%)	Industry (%)
Platform	38	50
Technical	40	53
Combat systems	18	68
Components	28	63
EPCM	3	78

Time Required to Reach Full Proficiency

An important consideration in reconstituting or developing a workforce is the amount of time it takes to "grow" a proficient workforce. Figure 7.3 shows the average number of years it takes for individuals within different technical disciplines to become fully productive. These estimates are based on the responses of the platform-design firms but are representative of the responses of the firms in the other groups.

Figure 7.3
Number of Years Needed for Technical Personnel to Become Fully Productive



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On average, it takes a technical person between three and seven years to become fully productive. This implies that a lead time of at least three years is required to train a draftsman or engineer.

Summary Views on Expanding the Workforce

Overall, some firms believe that there are several challenges to expanding their workforce; other firms believe that the supply of technical workers in Australia is sufficient to meet their future needs. Some of the problems mentioned in regards to expanding the workforce include the following:

- The uncertainty about future demands from submarine-design activities. Some firms felt that, once decisions were made on how the Future Submarine programme would proceed, they could begin to make workforce plans to meet the needs of the programme. Without a clear view of what was demanded of Australian industry, it is difficult for companies to plan their future workload needs.
- Competition from other industries for the same pool of technical resources. Many firms mentioned that many segments of Australian industry are expanding and some of these segments, such as the mining industry and the offshore market, are paying higher salaries and are therefore attracting skilled technical personnel. They also noted expansion within the Australian defence industry, mentioning the Joint Strike Fighter, the new AWD, and the future frigate programme.
- A finite supply of skilled technical workers. Many companies recognise that the supply of technical personnel in Australia is not unlimited, especially in some of the key specialised trades required during submarine design. They mentioned the limited

output of Australian universities in the engineering and naval-architect areas and cited the potential need to attract skilled technical personnel from other countries.

For of all these reasons, companies find it difficult to recruit mid-range and senior skilled engineers and naval architects, especially when faced with the requirement to obtain security clearances for the majority of their staff working on naval programmes.

Summary Estimate of Submarine-Experienced Personnel in Industry to Support a New Design

Although there are thousands of designers and engineers in Australia, estimating the total number of people in the Commonwealth who have the requisite skills and experience to work on submarine design is a challenge. Some individuals may have worked on a submarine programme at some point in their careers but have since been working on surface ships or other projects and have not maintained their submarine proficiency. Others may have some experience in a specific analytical capability that is useful to a submarine programme, such as computational fluid dynamics, but may have never worked on submarines.

Many of the companies we evaluated claim having some experience in the design, construction, or support of submarines. However, fewer had sustained revenues from submarine work, and even fewer had any workforce involved in submarine-design activities. Of the industry groups evaluated, the platform group received the largest percentage of revenue from submarine work—nearly 40 percent. The components group received nearly 25 percent of its revenue from submarine work, and the combat-systems group received around 10 percent. The platform and combat-systems groups had the largest proportion of their workforce involved in submarine-design activities, at 19 percent and 11 percent, respectively.

Previous RAND research has indicated that a core of submarine experience is required to successfully design a submarine.[2] As a result, we focused on estimating the total number of individuals with submarine experience. We further focused on the draftsmen and engineers who had submarine experience in the platform and technical firms. The platform firms will be the primary contributors to the design of the HM&E and will integrate the major systems and components into the design. The technical firms could contribute limited numbers of people to this effort. We assume that the EPCM firms have no relevant submarine experience. Draftsmen and engineers from these firms may be recruited and trained by the main HM&E design organisations, but we assume that they have no submarine-experienced personnel to add to the core upon which the design team will be built.

We assume that the combat system for the new submarine will be an existing military-off-the-shelf design or a modification of an existing system and will use commercially available components. The combat-system firms have experience in this area, personnel located in Australia, and the ability to incorporate personnel from their offices in other countries. Although the HM&E design team needs people experienced in combat-system integration, the majority of the combat-system design effort will occur outside of the platform-design team. Nevertheless, the submarine design and integration of the combat system into the submarine design will present major challenges, driving critical aspects of the design and requiring multiple trade-offs.

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2 John F. Schank, Jessie Riposo, John Birkler, and James Chiesa, *The United Kingdom's Nuclear Submarine Industrial Base*, Vol. 1: *Sustaining Design and Production Resources*, Santa Monica, Calif.: RAND Corporation, MG-326/1-MOD, 2005.

Finally, the major components of the new submarine will be procured from either Australian or international companies. The design effort for those components will be conducted by firms in the component group or by firms outside of Australia. Again, the platform-design team will need personnel experienced in the integration of components but will not have the lead design role for those components.

We estimate that there are approximately 480 individuals (210 draftsmen and 270 engineers) with current submarine experience available in Australia. This estimate includes a 5-percent inflation factor to account for firms that did not respond to the survey. Table 7.8 shows the number of draftsmen and engineers of various skills that are curently employed by the platform or technical firms. From the survey responses, we estimate that not all of these workers possess submarine experience.[3] For example, there are no HVAC engineers with submarine experience, and, in several skill categories—engineering management, fluids, planning and production, propulsion and power, and testing—there is only one individual with submarine experience.

Company projections showing growth and historical data on hiring and attrition indicate that these draftsmen and engineers will not be idle. The Future Submarine programme may face tough competition for experienced personnel resources, especially if companies growt their anticipated rates. Most companies indicate that they get the majority of their new hires from industry, but there will be a limited pool to draw upon if all companies are experiencing growth simultaneously. Additional hiring challenges identified include finding experienced and cleared individuals and having enough lead time to hire

[3] We estimate that the number of individuals with submarine experience, by skill category, is directly proportional to the ratio of draftsmen and engineers with submarine experience.

Table 7.8
Number of Technical Employees at Platform and Technical Firms, by Skill Category

	Skill Category	Number, by Skill	Number with Submarine Experience
Draftsmen	Arrangements	50	35
	Electrical	46	12
	HVAC	28	1
	Mechanical	75	45
	Piping	36	4
	Structural	62	12
	Other	143	96
Engineers	Combat systems and ship control	97	7
	Communications, sensors, and intelligence systems	56	1
	Electrical	112	16
	Fluids	35	1
	HVAC	31	0
	Management	55	1
	Material	6	2
	Mechanical	204	37
	Naval architecture	77	9
	Planning and production	29	2
	Professional support	493	160
	Propulsion and power	35	1

Table 7.8—Continued

	Skill Category	Number, by Skill	Number with Submarine Experience
Engineers	Signature analysis	9	4
	Structural	119	10
	Testing	4	1
	Other engineering	114	22

the required workforce. Under these conditions, it is expected that only a fraction of the experienced submarine draftsmen and engineers will be available to work on the Future Submarine programme. If we consider sustainable growth rates and mentoring ratios, between 100 and 200 draftsmen and engineers could be available to work on the Future Submarine programme without major disruptions to other work.

Facilities and Software Tools

In addition to personnel resources, we asked the industry organisations several questions about the availability of facilities and software tools needed during the design of a new submarine.

Facilities

The survey asked firms to report whether they had on-site access to a number of facilities that could support a submarine-design effort. The responses fell into four categories:

- most—facilities on site for more than 50 percent of the firms
- some—facilities on site for 30–50 percent of the firms

- few—facilities on site for less than 30 percent of the firms
- none—facilities on site for none of the firms.

Table 7.9 lists the facilities that were tracked by the survey in each category. Most firms possess the facilities expected of a design firm, but few have the facilities that would be necessary for building a naval vessel (specifically, a submarine). This suggests that the Government may need either to make investments in areas in which there currently

Table 7.9
On-Site Facilities

Most	Some	Few	None
Component/ system testing	Acoustic testing	At-sea test beds	Cavitation-research laboratory
Conferencing	Computing clusters	EMI/EMC and EMF testing	Combat-system shore facility
Integration testing	Non-destructive testing	Environmental testing	Confirmation hull-model testing
Model walk-through/ visualisation		Flood/damage testing	Damage-control trainer
Prototype manufacturing		Hydrostatic testing	Deep-submergence pressure testing
		Shock testing	Diesel-engine test bed
		Tow/hydrodynamics test tanks; conformation-model testing	High-pressure combustion spray chamber
			Model test basin
			Propeller testing (cavitation testing)
			Recirculating water channel
			Sensor testing
			Ship-handling simulator
			Torpedo analysis
			Weapons handling

are no capabilities or to make arrangements with other countries to utilise their facilities.

Table 7.10 shows the number of respondents that either had facilities on site or had access to needed facilities.

Table 7.10
Facilities Accessible to Design or Technical Firms

Facility	On Site	Can Access
Model walk-through/visualisation	11	7
Component/system testing	12	8
Integration testing	12	7
Conferencing	16	8
At-sea test beds	5	6
Prototype manufacturing	12	10
Non-destructive testing	6	13
Computing clusters	9	5
Tow/hydrodynamics test tanks; conformation-model testing	4	9
Shock testing	3	14
Flood/damage testing	4	6
Acoustic testing	7	11
Cavitation-research laboratory	1	0
Combat-system shore facility	1	0
Confirmation hull-model testing	0	1
Damage-control trainer	0	0

Table 7.10—Continued

Facility	On Site	Can Access
Deep-submergence pressure testing	0	1
Diesel-engine test bed	1	0
EMI/EMC and EMF testing	1	2
Environmental testing	1	1
High-pressure combustion spray chamber	1	0
Hydrostatic testing	1	1
Model test basin	1	0
Propeller testing (cavitation testing)	0	1
Re-circulating water channel	1	0
Sensor testing	0	2
Ship-handling simulator	1	0
Torpedo analysis	1	0
Weapons handling	0	1

Software Tools

A wide range of software tools is needed to design a submarine. These tools range from computational programmes for such areas as acoustics, structures, and hydrodynamics to complex, three-dimensional-modelling software. Table 7.11 lists various software tools, provides examples of commercial packages that provide the needed capability, and records the number of responses on the surveys that apply to the

Table 7.11
Availability of Commercial Software Tools

Software Tool	Examples	Number of Tools
Naval architecture		40
Submarine arrangements	Software: AutoCAD, CATIA, Siemens NX, Solidworks, SolidEdge	36
Applied mechanics	Software: DDAM, ABAQUS, NASTRAN, SIMULIA, CATIA	17
Shock qualification	Equipment: seismic air guns, British-designed systems Facilities: National Technical Services (U.S.), Hi-Test Laboratory (U.S.)	3
Structural analysis	Software: 3D design tools	40
Fluid dynamics		22
Hydrodynamics	Software: NAVSEA Concept Visualisation system Equipment: instrumented models, tow models, LSVs (U.S.) Facilities: tow tanks (U.S. and Australia)	17
Fluid systems	Software: fluid models Equipment: test-loop equipment	9
Pipe stress	Software: NASTRAN variants (from NASA, NEi NASTRAN, Siemens PLM Software), ROH2	10
Mechanical systems	Software: AutoCAD, CATIA, Siemens NX, Solidworks, SolidEdge	24
Propulsion systems		2
Acoustic analysis		3
Structural acoustic analysis	Software: ABAQUS/Simulia Equipment: LSVs Facilities: Applied Physical Sciences (U.S.)	3

Table 7.11—Continued

Software Tool	Examples	Number of Tools
Software development		22
Sonar engineering		
Radar		
Systems engineering		25

specific tools. As can be seen from the table, a wide range of software tools currently resides within Australian industry or, in terms of facilities and equipment, may be available from the United States.

CHAPTER EIGHT

Design Personnel, Facilities, and Software Tools Available Within the Australian Government

In this chapter, we discuss our analysis of the submarine design resources within Australian Government organisations. For this line of inquiry, we surveyed and interviewed a range of Government offices, divisions, and directorates.[1] We also engaged Government organisations that are responsible for non-submarine maritime programmes and systems; this helped us understand what resources are available and are generally, if not specifically, relevant to submarine design.[2]

We used the same survey that we distributed to industry (described in Chapter Six). The surveys and interviews allowed us to characterise the roles that different Government organisations may play in the

1 We surveyed and interviewed the DMO Directorate of Submarine Engineering (DSME), the DSTO Marine Platforms Division (MPD), the Maritime Operations Division (MOD), and the Submarine Combat System Program Office (SMCSPO). We sent surveys to, but did not receive responses from, the Collins Program Office (COLSPO), the Office of Director General Submarines, the DMO Maritime Systems Division (MSD), and the RAN Commander of Submarine Force. Based on interviews, we believe that the surveys we received account for the vast majority of Government resources presently devoted to issues of submarine design and sustainment.

2 Specifically, we interviewed Government representatives from the AWD Alliance and gathered data about non-submarine maritime-engineering personnel within DMO and the Office of the Chief Naval Engineer (CNE).

design of the Future Submarine, the size of the Government workforce that is currently available, the distribution of available personnel across important skill categories, the years of experience and turnover of the workforce, the demands on the Government workforce that will come about in the future, the ability of organisations to grow, and the available design and test facilities.

Because organisations may combine or divide, and because their responsibilities are subject to change, our analysis was concerned with total Government resources rather than with the resources committed to a particular organisation or devoted to a given role. We distinguished surveyed organisations only to highlight where resources are presently located within the Government.

The Roles of Government Organisations

All surveyed organisations contribute to the in-service support of *Collins*-class submarines and have resources that could contribute to the design of a future submarine. However, the organisations' specific roles in submarine design differ, as the organisations reported in the surveys and clarified during interviews.

DSME provides design-certification services and engineering support to the submarine programme offices and has been delegated design authority by the CNE. Specifically, DSME helps specify requirements, assess contractors, conduct design reviews, and develop test and sea-trial documentation. Presently, DSME is exclusively dedicated to *Collins* in-service support.

DSTO provides technical expertise and support to the programme office, particularly in cases in which the necessary expertise exceeds what is available at the programme office, at DSME, and through contractors. Specifically, DSTO performs technical-risk assessments, design-performance evaluations, and design-review analyses. It also prototypes systems. DSTO acts as the primary Department of Defence interface between DMO and technical resources in academia, and it often supports academic facilities and laboratories. DSTO also serves as a conduit to science and technology organisations in other countries. DSTO resources support RAN surface-ship programmes.

The SMCSPO manages the design of an integrated submarine combat system, receiving support from sub-system suppliers. In contrast to DSME, SMCSPO provides integration and system-level engineering. As part of its design management, SMCSPO is responsible for system-level product requirements, system architectures, configuration management, system-test plans and proceedings, and system certification.

Personnel Resources

Table 8.1 compares the number of Government engineers, scientists, and technical personnel who are presently dedicated to design or sustainment with the number dedicated to other maritime design or sustainment.[3] Across responding organisations, 173 full-time equivalent engineers, scientists, and technical staff members are dedicated specifically to submarine design or sustainment. This workforce represents approximately 28 percent of the Government's maritime-related technical community.

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[3] Table 8.1 does not reflect DSTO personnel who are dedicated to non-submarine maritime science or technology; this information was not available at the time of writing. In addition, we subsequently learned that the COLSPO has been reorganised and now has three submarine-experienced personnel. This reorganisation is not reflected in Table 8.1.

Table 8.1
Number of Government Engineers, Scientists, and Technical Personnel Presently Dedicated to Submarine or Other Maritime Design or Sustainment Activities

Organisation	Submarine Personnel	Other Maritime Personnel
DMO	87	391
DSTO	86	0
Navy	0	63
Total	173	454

The remainder of this chapter focuses on this workforce, which consists of Government engineers, scientists, and technical personnel who are presently dedicated to submarine design or sustainment (hereafter the "submarine workforce"). The surveys allowed us to measure the distribution of this workforce across Government organisations; the distribution of technical personnel across skill categories relevant to submarine design; the average age and experience of the personnel; and how much the technical staff changes as a result of hiring, retirements, reductions, etc. We will revisit the ability to leverage personnel resources associated with other maritime (i.e., surface-ship) programmes when we evaluate options for closing the gap between the Government resources needed and those available.

Table 8.2 depicts the distribution of the submarine workforce across DSME, DSTO, and SMCSPO. The data suggest that 50 percent of the Australian Government's submarine-design personnel reside

Table 8.2
Number of Government Engineers, Scientists, and Technical Personnel Presently Dedicated to Submarine Design or Sustainment, by Organisation

Organisation	Employees	External Service Providers
DSTO	86	0
DSME	21	0
COLSPO	0	0
SMCSPO	48	18
Total	155	18

within DSTO and that more than 40 percent of existing personnel are dedicated to combat systems.[4]

SMCSPO recorded that 38 percent of its staff is provided by external service providers (ESPs).[5] In follow-up interviews, DSTO mentioned consulting with academic experts but indicated that no more than 10–15 percent of its staff at any one time is provided by ESPs. With the exception of SMCSPO, none of the responding organisations reported significant use of ESPs, and they did not include ESPs in their counts.

4 SMCSPO personnel are clearly associated with combat systems, and they account for 38 percent of the surveyed government submarine design-related workforce. A portion of the DSTO personnel are also associated with combat systems, but the survey data as collected do not allow us to distinguish individuals associated with combat systems from individuals associated with ship control. Additional interviews may clarify this point.

5 Since this report was written, the Collins Submarines Branch at DMO has been reorganised, and ESP positions are now occupied by public servants. The reorganisation has had no effect on the number of engineers working on *Collins* issues.

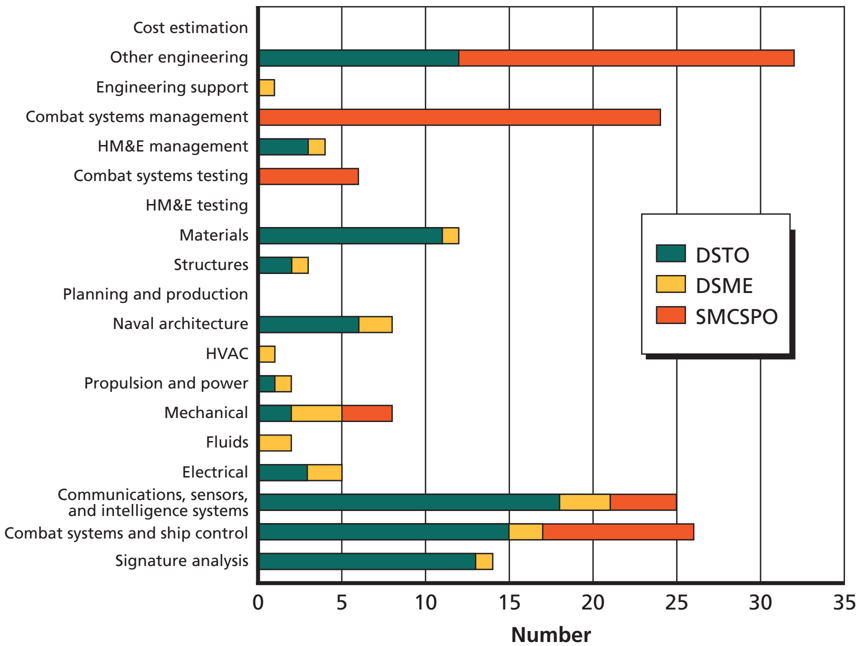
A comparison of personnel resources at DSTO and DSME suggests that there are disproportionate resources in science and technology compared with resources directly related to design certification and engineering support: DSME has 24 percent of the personnel resources of DSTO. Our experience with U.S. and UK submarine designs indicates that engineering, rather than purely science and technology, is most critical for submarine design. Because DSME has only one-quarter of the personnel resources that DSTO has, it could not support an Australian design process. This is not to say that DSTO support should be reduced; rather, DSME support needs to be increased.

Figure 8.1 shows the distribution of the submarine workforce across skill categories.[6] The largest amount of resources is associated with combat systems (including combat-system management and testing), reflecting the ongoing design efforts within SMCSPO. Within HM&E skill categories, the largest numbers of engineers are in structures and material, naval architecture, communications systems, ship control, and signature analysis. In the critical areas of propulsion, mechanical, and electronic systems, there are noticeably few Government resources. The Government did not identify a single individual in cost estimation, planning and production, or testing.

The age and naval and submarine experience of an engineer provide a measure of capability, assuming that more experience correlates with increased qualifications. Figure 8.2 shows the average years of experience in both the naval and submarine sectors for each skill cat-

[6] The skill categories represent a combination of categories that appear in the survey (see Appendix E) and an alternative set of categories provided by SMCSPO. The survey instrument did not request counts of cost estimators, but the topic was approached in follow-up interviews.

Figure 8.1
Number of Government Engineers, Scientists, and Technical Personnel Presently Dedicated to Submarine Design or Sustainment, by Skill Category



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egory.[7] As a point of comparison, respondents noted that between two and five years of experience is required for an individual to be fully productive. Moreover, the data suggest that the workforce is relatively

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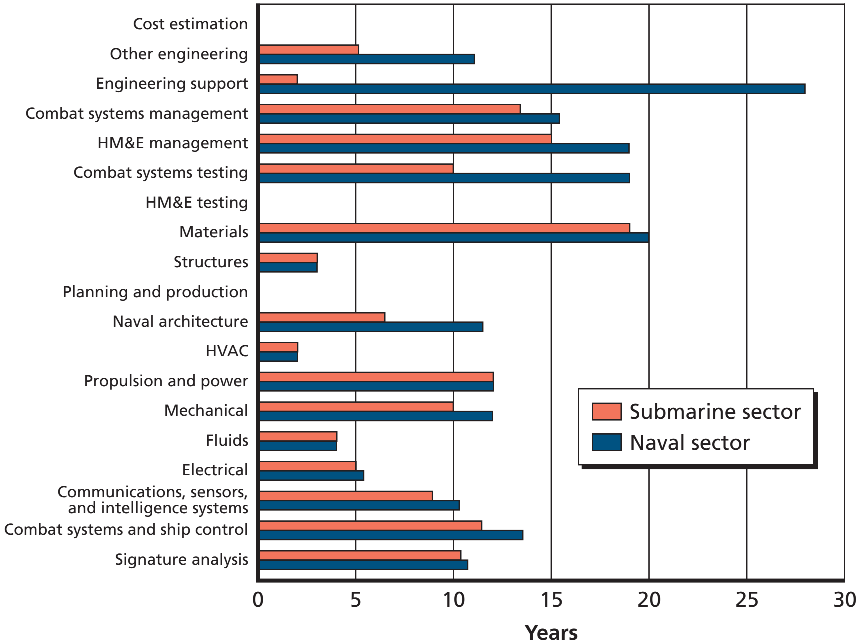
7 To estimate the averages, we used upper bounds rather than averages when respondents provided age ranges. If one respondent did not provide age estimates for a given skill category, we excluded that category from the cross-respondent average.

Figure 8.2
Years of Experience Design, Construction, and Support in Government, by Skill Category



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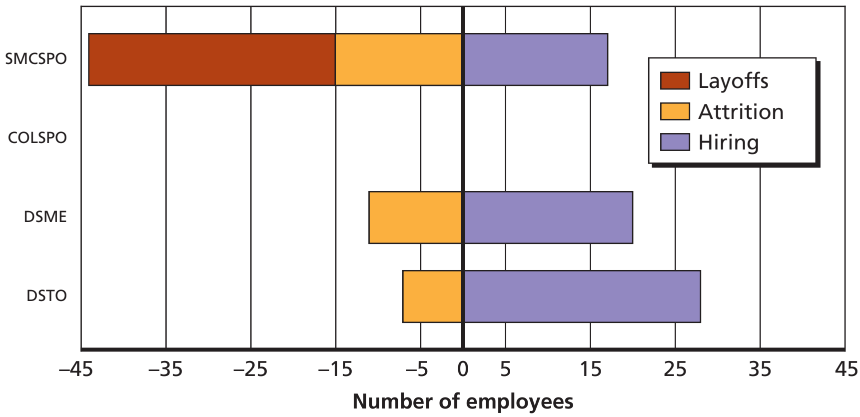
young—the average age is 43 years—and relatively few individuals are over the age of 60 (7 percent).

Figure 8.3 depicts the number of personnel hires, retirements and departures, and reductions in responding organisations from 2005 to 2009. The data suggest that the technical workforce has decreased at SMCSPO and increased at other organisations. However, our interviews clarified that the reduction in the combat-system workforce was due, in part, to the expiration of ESP contracts. SMCSPO indicated that it plans to transfer ESP positions to full-time employees.

Figure 8.3
Number of Engineers, Scientists, or Technical Staff and Scientists Gained or Lost, by Government Organisation



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The resources available to the Government through reach-back to allied countries are not reflected in these data. Australia is presently collaborating with the United States on the *Collins*-class combat system. In principle, this reach-back capability could be leveraged if the Future Submarine design is an all-Australian effort. But if the Future Submarine relies on an evolution of a foreign submarine design or a non-U.S. combat system, then assistance from the United States is severely limited and intellectual property issues come to the fore.

Ability to Expand the Workforce

The responding organisations did not detail plans to expand their technical workforce. However, respondents provided information that allowed us to qualitatively assess their capacity for growth.

Every responding Government organisation reported Government limits ("caps") on hiring and indicated that the current number of staff is near or at the limit. Hiring ESPs was identified as an approach to expand the workforce beyond Government limits, but SMCSPO was the only organisation that reported extensive use of ESPs. DSTO reported using ESPs on occasion but noted that ESPs never account for more than 10 to 15 percent of its workforce. However, agencies have only limited options for expanding the use of ESPs, which, combined with public servant gaps, severely constrains workforce growth.

The availability of interesting and challenging work was described by most surveyed organisations as a factor that limits the ability to attract and retain technical personnel. Presumably, this reflects the present state of the *Collins* programme, and a Government strategy to pursue the Future Submarine may alleviate this issue.

Competition with industry and workforce mobility emerged as two other limiting factors. Off-shore mining industries attract engineers (particularly naval architects) who might otherwise be attracted to DSME or COLSPO. Major software and hardware firms compete with SMCSPO for electrical engineers and information technologists. Organisations indicated that, in the past, it has been difficult to recruit Australians to work away from where they live, suggesting that an immobile workforce may present a further barrier to growth.

Some organisations mentioned that the unavailability of senior staff to mentor new staff acts as a constraint: Senior staff who are assigned the role of mentoring new hires are prevented from doing their regular jobs. Surveys indicate that new Government hires in oversight or management roles require at least one year and sometimes up to five years to become fully proficient. Thus, hiring new employees may reduce capacity in the short term until new staff gain enough experience to make up for the time senior staff spend mentoring.

Finally, DSTO, which is traditionally a preferred employer for many graduate-level engineers and scientists, indicated difficulty in hiring technical staff with submarine experience.

Estimating Future Workforce Demand

Survey responses from Government organisations did not indicate anticipated future demand on their workforces. However, unlike the commercial sector, where non-naval projects can create workforce demands, Government organisations support only DMO projects. Thus, we can characterise future workforce demand in terms of current and future programmes that may leverage the same resource pool.

Technical personnel with experience working on the *Collins* class are perhaps most valuable to the Future Submarine programme, given the value of understanding issues specific to submarine design. However, technical personnel associated with non-submarine maritime programmes may also be attractive because they may require less training than individuals with no such maritime experience, and they have transferrable technical skills. For similar reasons, surface-ship programmes could draw on submarine personnel. Thus, we consider both submarine and surface-ship programmes when assessing future demands on the technical workforce.

The *Defence White Paper 2009* articulates a broad modernisation of Australian maritime assets. Any consideration of future workforce demands should include these planned programmes. The primary programmes specified in the white paper include

- the replacement submarine programme (the Future Submarine)
- upgrades to the *Collins* class (SEA 1439 and SEA 1329)
- the AWD programme (SEA 4000)

- landing helicopter dock (LHD) ships (Project JP2048)
- upgrades to the *Adelaide*- and *Anzac*-class frigates (SEA 1390 and SEA 1448)
- the Future Frigate programme (SEA 5000)
- modular offshore combatant vessels (SEA 1180).

Many of these projects overlap with the design and build time lines of the Future Submarine programme. Within the undersea-platform community, in-service support and planned upgrades to the *Collins* class coincide with the design of the Future Submarine. Within the surface-platform community, a series of upgrades and new designs occurs concurrently with these planned upgrades and the design of the Future Submarine. The first AWD ship is due to be delivered in 2014, the first LHD in 2013; the upgrade to the *Anzac*-class frigates runs from 2010 to 2018; and the Future Frigate programme has an initial operational capability date of 2025.

Design Tools and Facilities

Table 8.3 shows the design and test facilities that these Government organisations maintain. Survey responses indicated the presence (or absence) of a facility, but a comprehensive assessment of each facility's ability to support a new submarine design was beyond the scope of the project.

Several additional facilities are maintained at the Australian Maritime College (AMC) with funding support from DSTO. The SMCSPO maintains an independent system integration and testing facility for combat systems.

Table 8.3
Design and Test Facilities Maintained by Surveyed Organisations

Facility/Resource	Organisation
At-sea test beds	SMCSPO
Underwater sensor testing	SMCSPO
Combat-system shore testing, training facility	SMCSPO
Torpedo-analysis facility	SMCSPO
Acoustic-measurements facility	DSTO
Shock testing	DSTO
Submarine combat-system laboratory	DSTO
Maritime-experimentation lab	DSTO
Land-based test facility	DSTO

Finally, the surveys indicate that between DSTO, DSME, and SMCSPO, the Government has access to, or could readily gain access to, any needed software-design tools.

Available Government Resources: Summary

The foregoing analysis admits an assessment of the Government resources in Australia that are presently associated with submarine design and support. Our analysis is limited by the nature of surveys and interviews to primarily assessing the quantity of resources, and only through the proxy of experience can we assess their quality. Nonetheless, the data allow us to make a number of conclusions.

Broadly speaking, our surveys of and interviews with Government organisations suggest that there are significant and experienced submarine-design personnel resources available. Across skill categories relevant to submarine design, the most-significant capability resides in combat systems, no doubt reflecting the ongoing *Collins* combat-system programme. Notwithstanding the issue of integrating and testing an evolved *Collins*-class combat system into a new submarine design, the data suggest that there are sufficient personnel to install and test an existing or modified combat system on the Future Submarine.[8]

In contrast, HM&E organisations appear to have significant breadth but less depth. For example, there are few (if any) Government personnel specializing in the areas of propulsion, fluids, electrical systems, cost estimation, testing, and planning and production. We expect the aforementioned skill categories to be increasingly important if Australia pursues an indigenous design and transitions to parent-Navy status. Thus, the data may foreshadow a capability gap when a future submarine is designed.

In several skill categories, such as naval architecture, materials, and communications systems, the available resources reside primarily within DSTO. To the extent that DSTO may focus on science and technology, this point raises a question about the Government's ability to serve the design-review and engineering-support roles typically assumed by DSME and the programme office.

Experience has shown a number of skills to be important for successful programmes, but they are impossible to identify through surveys and short interviews. For example, supporting a design requires significant expertise and experience in the management of complex

[8] This conclusion reflects our guidance from the Future Submarine Program Office noted earlier that the Future Submarine will use an off-the-shelf combat system.

projects. The number of needed individuals may be small, but their impact can be large.

As described in the *Defence White Paper 2009,* several modernisation programmes are competing for the personnel resources required by the future submarine programme. On the one hand, these programmes may provide points of leverage to the extent that certain naval-engineering skills are transferrable between surface-ship and submarine programmes. On the other hand, these programmes may compete for the most-experienced technical personnel within the Government. In all cases, any assessment of capability gaps must account for these competing demands and reflect that existing personnel are fully employed. To this end, future analysis will need to consider strategies for overcoming the barriers to growth identified during the surveys.

Notably, we did not receive survey responses from the Collins Program Office, and our statistics therefore undercount the Government personnel resources. In principle, our findings could change. However, based on our interviews, we do not expect that these missing data will qualitatively affect the results.

CHAPTER NINE

Design Personnel, Facilities, and Software Tools Available in Australian Academic Institutions

In this chapter, we discuss our analysis of design resources that are available in Australian academic institutions. To conduct this analysis, we used the same survey that we distributed to industry (described in Chapter Six). We surveyed three institutions: AMC, the University of Adelaide, and the University of Melbourne.[1] We also interviewed dispersed faculty at AMC, the University of Adelaide, the University of South Australia, Flinders University, Monash University, Deakin University, the Royal Melbourne Institute of Technology, Swinburne University, and the University of Melbourne.

The responses that we received allowed us to characterise the available facilities and the available workforce in terms of size, the distribution of available personnel across important skill categories, years of experience, and turnover.

In general terms, we found that the skill mixes at universities might allow them to play one or more of four roles in designing a future submarine by providing industry and Government with the following:

[1] We received a survey response from AMC and a modified response from the University of Adelaide.

- technical expertise through faculty and senior research staff
- facilities and laboratories that can support design certification and testing
- education for the current and future technical workforce
- technology innovation that may drive what systems or components can be incorporated into the design.

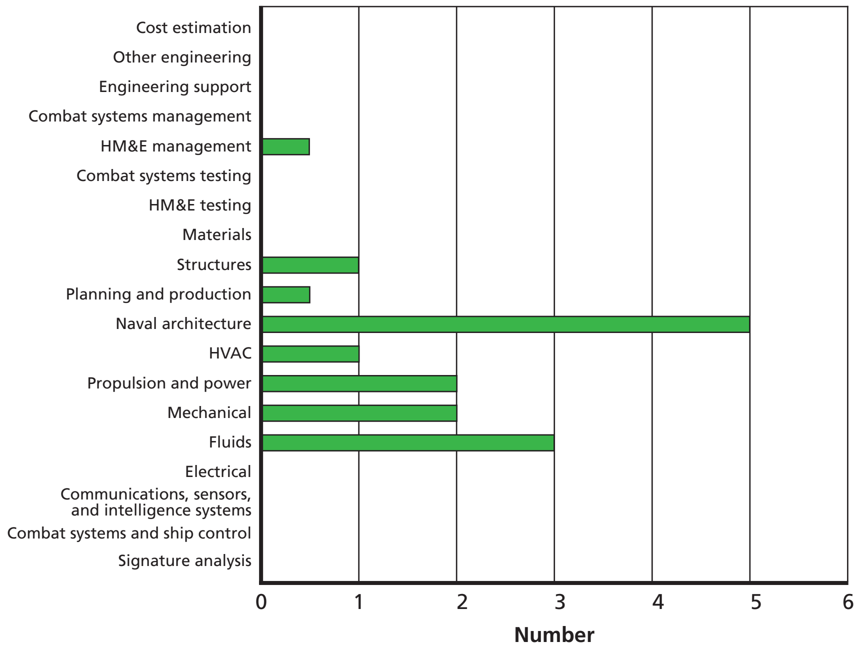
Technical Expertise

A thorough evaluation of the Australian academic research enterprise was beyond the scope of our project. However, AMC was identified as the key academic source for naval-architecture, maritime-engineering, and ocean-engineering expertise, and our survey allowed us to characterise its resources.

Figure 9.1 depicts the numbers of faculty and research staff by skill category.[2] Figure 9.2 indicates the percentages of AMC and Government personnel. The data suggest that, in absolute terms and relative to Government personnel, AMC has significant capability in naval architecture and fluids. Interviews suggest that AMC has particular strengths in hydrodynamics and manoeuvring and could support computational and experimental analysis of hull forms, including surfaced and submerged hydrodynamics testing. Moreover, AMC has a history of collaborating with industry and Government (including DSTO).

[2] Some faculty and research staff naturally fit into multiple categories. In these cases, an individual was divided across categories according to how much time he or she spent conducting such research. That is, the numbers reflect FTEs.

Figure 9.1
Number of Engineers at AMC, by Skill Category



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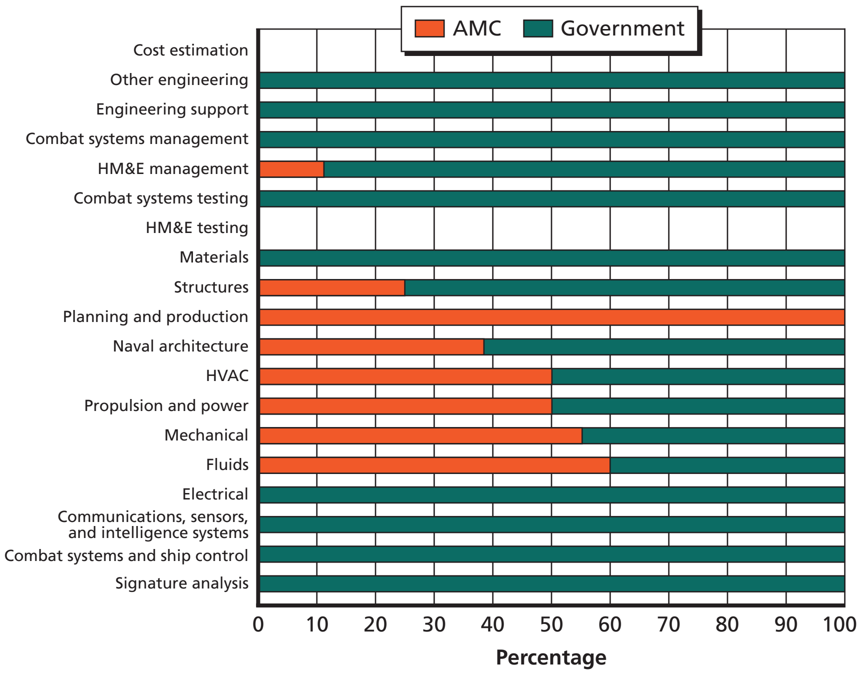
Supported in part by the South Australian government, the Defence Systems Innovation Centre (DSIC) is a joint venture between the University of Adelaide and the University of South Australia. The centre's aim is to become a national centre for defence research and education, and it is soliciting seed funding from industry players. The University of Adelaide brings capabilities in networking, simulation, and modelling, and the University of South Australia offers expertise in systems engineering/integration and testing. Perhaps most relevant to the Future Submarine programme, the centre may provide a struc-

Figure 9.2
Percentage of AMC and Government Personnel, by Skill Category



RAND *MG1033-9.2*

ture for collaboration between the Department of Defence and South Australian universities: Experience has shown that structures such as these facilitate the exchange of expertise between academia and Government.

Other Australian universities, particularly those in the "Top Eight", surely offer additional capacity to provide scientific and engineering expertise that is generally if not specifically relevant to submarine design. In contrast to AMC, where expertise is concentrated within a co-located faculty, academic expertise across other universities may be more dispersed across departments. For example, there are faculty members with expertise in permanent magnet motors in the Department of Mechanical Engineering at the University of Adelaide and in battery technology at Monash University. Engaging dispersed faculty may prove more challenging than engaging faculty in organisations such as AMC and DSIC, although there surely is a precedent for DSTO to consult individual academics.

Facilities and Laboratories

AMC has several facilities that could support design verification of a future submarine:

- towing tank
- model test basin
- cavitation-research laboratory
- recirculating water channel
- high-pressure combustion spray chamber
- diesel-engine test bed
- fisheries research and training vessel—*Bluefin*
- damage-control trainer
- ship-handling simulator.

Several of the facilities are supported through DSTO. The facilities are sized to support model testing. AMC reported having a capacity to "rent" facilities to industry or government and indicated a history of doing so (e.g., for the America's Cup).

Institutions with Maritime or Defence Programmes

For reasons of scope, we did not assess the capability or the capacity of the Australian educational system, broadly conceived. Rather, we focused more narrowly on a subset of universities and colleges that have programmes or departments in maritime- or defence-related science and engineering.

In this regard, AMC once again appears unique, offering both undergraduate and graduate-level courses in naval architecture, marine and offshore systems, and ocean engineering. In addition, AMC offers a postgraduate unit called "Design of Maritime Machinery Systems". Undergraduate-level students graduate at a rate of roughly 40 students per year, and there are approximately 20 Ph.D. students in residence. In interviews, AMC indicated a capacity to expand, perhaps even double, student enrollments in the short term. AMC noted that recruiting students is a potential limiting factor, suggesting that the very long time line of designing, building, and delivering a submarine may dissuade students interested in the nearer-term rewards that are available in the oil and mining industries.

The University of Adelaide also offers a master's degree in marine engineering. Flinders University, in conjunction with AMC, offers programmes in maritime electronics, naval architecture, and ocean engineering.

Technology Innovation

In some scenarios, academia plays an additional role: driving technological innovation through research. Such innovation may affect what systems or components can be incorporated into a submarine design and, ultimately, the performance of the submarine once designed.

For example, research conducted at universities may lead to advances in fuel-cell technology that enhance the range or submerge time of a future submarine.

However, academic research tends towards the fundamental, and, typically, much more engineering is required before laboratory demonstrations reach the level of technological maturity necessary for submarine design. More generally, experience has shown that defence research is sufficiently specialised and sensitive that Government research organisations (e.g., DSTO) are a more significant source of the kind of innovation that contributes directly to submarine design. Information gathered from Australian universities is consistent with this experience.

In principle, academia could play a larger role in driving the kind of innovation that supports the design of a future submarine. However, such a role is likely to require government support and engagement, which would allow academia to become aware of necessary requirements and design constraints and receive the funding required to support fundamental research. The ability of AMC to support the design and certification of the Future Submarine hull is the result of its long-term engagement with DSTO.

Available Academic Resources: Summary

AMC offers significant expertise and facilities that both industry and government could leverage in designing a future submarine. AMC's expertise is particularly strong in computational and experimental modelling of hydrodynamics, with a tow tank, model test basin, and cavitation tunnel. AMC may most directly contribute to design certification and testing of hull designs. AMC has a history of supporting both industry and government and, thus, appears well positioned to support the Future Submarine.

Other generally relevant expertise may be more dispersed across universities and academic departments. The Future Submarine may be able to leverage these centres of expertise, but the challenge may lie in engaging and managing the distributed resources. The emerging DSIC venture between the University of Adelaide and the University of South Australia provides another model for such interaction between the Government and academia.

CHAPTER TEN

Specifying Australia's Submarine Design Resources Gap and Defining Options to Close It

In this chapter, we first define the gap in submarine design resources facing the Future Submarine programme based on our estimates of the resources needed for a new submarine design and the current design resources that exist in Australia. We then identify various options for closing the gap in personnel resources in both industry and the Government and the gap in facilities and software tools.

Gap in Personnel Resources

Industry Personnel

We focus on the gap in submarine design personnel amongst the platform and technical expertise organisations. These are the firms that would be the primary contributors to the team that designs the basic HM&E of the new submarine and that integrates the major systems and components. Table 10.1 shows the peak demand (from Chapter Three) and supply (from Chapter Seven) for the draftsmen and engineers in these firms.

Table 10.1
Low and High Estimates of Industry Personnel Peak Demand and Supply[1]

	Peak Demand		Supply	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Draftsmen	289	432	40	80
Engineers	324	485	55	110

As discussed previously, our demand estimates assumed that the development of the combat system and certain other systems and components, such as the propulsion and power train, may not be the responsibility of the firm that designs the basic platform. The platform design firm must integrate those systems into the total submarine design, but the systems and components themselves would be provided by other organisations. The exact systems and components that will be used on the Future Submarine have yet to be determined. Some may be designed specifically for the Future Submarine, others may be purchased from domestic or foreign vendors. Thus the numbers we report here do not reflect the total number of personnel required to design all systems and components that comprise a complete, battle-ready vessel.

Table 10.2 shows the total number of skilled draftsmen and engineers available in Australia with submarine experience and the peak demand for those skills for the 8 MMH and 12 MMH demand esti-

[1] The supply numbers shown here differ from those shown in Table 7.2 and elsewhere in Chapter Seven because here we estimate how many people might be available to work on the Future Submarine programme, recognising that they are all currently employed on other programmes. We use 40 percent as an upper bound and 20 percent as a lower bound. We count only the platform and technical groups (because of our assumption that the combat system and component people will develop their own products and pass them to the platform group).

Table 10.2
Submarine-Experienced Draftsmen and Engineers Available in Australia and Peak Demands, by Skill Competency

	Skill Competency	Number Available	Maximum Demand	
			8 MMH	12 MMH
Draftsmen	Electrical	12	64	96
	Mechanical	45	39	58
	Piping/HVAC	5	58	86
	Structural/arrangements	47	89	134
	Other	96	39	58
Engineers	Signature analysis	4	20	29
	Combat systems and ship control	7	51	77
	Electrical	16	39	58
	Fluids	1	26	39
	Mechanical	37	26	39
	Naval architecture	19	64	96
	Planning and production	2	13	20
	Structural/arrangements[a]	—	—	—
	Testing	1	7	10
	Management	1	13	20
	Engineering support	160	26	39
	Other engineering	22	39	58
Total		475[b]	613	917

[a] Grouped with naval architecture.

[b] Demands from other programmes may result in few (if any) personnel being available to support a new submarine design.

mates. Note that the number of people with submarine experience in Australia does not imply these personnel are available to support the new submarine programme. Demands from other programmes will require the services of most, if not all, of these personnel.

There are fewer individuals than what is required at the peak in all but the Other Engineering and Professional Support skill categories. Other skill categories have varying levels of personnel; some have near peak levels while others have significantly fewer than what is required at the peak. The Mechanical and Electrical Engineering skill categories have almost as many as are required at the peak of a 12 MMH design effort. The Electrical and Piping drafting trades have less than one-third of the peak design requirement. Less than one-third of the peak design requirement is available in the Fluid Engineer, Naval Architect, Planning and Production, and Signature Engineer skill categories.

Government Personnel

At first glance, our analysis of the supply of Government personnel resources suggests that the total number of personnel is sufficient to meet the estimated demand of 85 to 175 personnel. Across DMO and DSTO, our surveys indicate that there are more than 173 engineers currently associated with submarine design. The Government's existing submarine design workforce has a significant amount of experience from the *Collins*-class programme and has special capability in combat systems due to the design responsibilities assumed by SMCSPO. Moreover, there are about 450 engineers working within DMO and the CNE on non-submarine maritime programmes; these individuals may have expertise that is generally if not specifically relevant to submarine design.

However, this broad look across the Australian Government ignores two important gaps in the existing resources. First, existing personnel are "fully employed" supporting the *Collins* class or other

RAN programmes, and thus they cannot contribute to a new submarine design without a risk of consequences for ongoing RAN programmes. Strategies for building the Government workforce for the Future Submarine should not assume that existing staff is available without assessing the consequences of taking them away from ongoing programmes.

Second, surveys indicate that there are too few personnel in skill categories anticipated to be important in the design of a future submarine. In particular, few if any resources exist in the areas of propulsion, fluids, electrical systems, cost estimation, testing, and planning and production. Moreover, in other skill categories such as naval architecture, materials, and communications systems, the available resources reside primarily within DSTO; this point raises the question of the Government's ability to serve the design review and engineering support roles typically assumed by DSME and the programme office. These skill categories are expected to be increasingly important if Australia pursues a domestic design and transitions to parent Navy status. Thus, assuming the Australian Government will maintain a level of technical authority in the Future Submarine, strategies for building the Government workforce should address the need to develop capability in these areas where expertise is currently lacking. It should be noted that the Government will require these skill categories as it maintains these submarines over their lifetime.

Gap in Skills and Technology

In this section, we focus on potential gaps in engineering and management skills and technology. Instead of looking at skill sets for industry, Government, and academia separately, we look broadly at capability within the Australian maritime complex. The gap analysis looks at skills within three functional technology areas relevant to submarine design: combat systems, hull form design, and HM&E systems. Propeller design issues fall into both hull form and HM&E categories. Combat systems include the fire control system (for example, the AN/BYG combat system on the *Collins* class), the sonar system, and internal and external communications systems. Hull form design is mainly concerned with those naval architecture and hydrodynamic skills related to designing the final hull form. Finally, HM&E refers to design skills pertinent to systems contained within the outer hull form.

The available personnel across skill categories for industry, Government, and academia are shown in Table 10.3. For the purposes of this analysis, the resources from academia reside exclusively at the Australian Maritime College. As noted in Chapter Nine, there are likely to be individuals dispersed across Australian universities who have expertise in the areas of interest, but they are not included in this table. The number of engineers available within industry is further broken down between those with submarine experience and those with maritime but not submarine experience. Government organisations with maritime but not submarine experience were not surveyed to discern individual skill categories. There are approximately 450 individuals in Government organisations with non-submarine maritime experience.

In the area of combat systems, there are significant numbers of engineers with submarine experience in industry and Government. In addition, a substantial number of non-submarine combat system engineers are available within industry. As discussed in Chapter Eight, the Government maintains numerous facilities within the SMCSPO and at DSTO to support combat-system development. Finally, the Government reports 24 management positions and six testing positions dedicated to combat system design and development. This large and experienced workforce reflects the ongoing *Collins*-class combat systems programme. Notwithstanding the issue

Table 10.3
Engineering Skills for Industry, Government, and Academia

Skill	Industry: Number by Skill	Industry: Number with Submarine Experience	Government	AMC
Combat systems and ship control	1,302	210	26	0
Communication, sensors, intelligence systems	56	1	25	0
Naval architecture	77	19	8	5
Fluids	35	1	2	3
Signature analysis	9	4	14	0
Propulsion and power	35	1	2	2
Electrical	112	16	5	0
Mechanical	204	37	8	2
Material	6	2	12	0
Structural	119	0	3	1
HVAC	31	0	1	1
Planning and production	29	2	0	1
Testing	4	1	0	0
HM&E testing	0	0	0	0
Combat system testing	0	0	6	0
Management (total)	55	1	28	1
HM&E management	0	0	4	0
Combat system management	0	0	24	0
Other engineering	114	22	32	0
Engineering support	493	160	1	0

of integrating an evolved *Collins*-class combat system into a new submarine design, the data suggest that there are sufficient personnel to accommodate combat system design and integration.

In the area of hull form design we focused on naval architecture, fluids, and signature analysis. Engineers associated with naval architecture who have submarine experience are evenly spread across industry, Government, and academia. Based on our interviews, we believe there has been a dedicated effort to expand the technical base within Australia to support hydrodynamic research. This is evidenced by the construction of facilities at AMC and increasing collaborations amongst DSTO, AMC, and overseas allies. In terms of fluids, which refer primarily to computational fluid dynamics, the preponderance of talent is found within Government and academia. Finally, in these skill categories, we identified more than 100 engineers within industry who had non-submarine maritime engineering experience. The data suggest that a gap may be present in hull form design, but investment in Government and academic organisations can assist in the final design process.

In contrast, HM&E design appears to be characterised as having significant breadth but minimal depth. In the areas of propulsion and power, structures, and HVAC, there are fewer than ten people with submarine engineering experience in either industry or Government. Of most concern, the propulsion and power industry reported a single engineer and Government only two people. In all three skill areas, industry has more substantial resources available with non-submarine maritime engineering experience. However, as evidenced by the *Collins* class experience, propulsion issues on a diesel-electric submarine tend to require a high degree of specialisation relative to surface ships. In the areas of electrical and mechanical engineering skills, industry has more individuals with submarine experience and numerous engineers with non-submarine maritime experience. In addition to the lack of submarine-experienced engineers in the HM&E design area, surveys and interviews suggest a lack of facilities to develop and test these systems. While there are several ongoing investments in the areas of combat systems and hull form engineering, there appears to be little investment in facilities dedicated to propulsion and energy systems within industry, Government, or academia. In particular, there are no facilities to support the development of advanced energy generation (diesels), energy storage (batteries and/or AIP systems), electrical distribution, and propulsion. We expect the aforementioned skill categories to be increasingly important as Australia pursues a domestic design that envisions increasing propulsion requirements. Thus, the data may foreshadow a capability gap for the prospect of designing the Future Submarine.

Engineering and technical skills do not cover the entire skill set required for a successful design. Successful submarine designs rely on experienced and talented managers, as well as testing capacity, to evaluate the designs. In the area of planning and production, industry reports a single person with submarine experience while the Government reports none. In the area of testing, industry reports a single person with submarine experience while the Government reports no personnel in non-combat system testing. Finally, in the area of management personnel, industry again reports a single person while the Government reports four people with submarine experience. In the areas of testing and management, the Government reported significantly more resources dedicated to combat system development. Determining the impact of inexperienced personnel in planning, testing, and management is speculative. However, submarine design and production tend to require significant system-level experience, suggesting a capability gap in these areas.

Options for Closing the Personnel Gaps

Industry Options

Even under the best of assumptions on the supply of experienced personnel available in Australia to undertake a new submarine design, substantial additional numbers of draftsmen and engineers are needed in industry to complete the design effort. If the total man-hour demand over the duration of the design effort for experienced personnel is fixed, there are basically two alternatives for closing the gap—expand the submarine design workforce with only Australian personnel or infuse new personnel from other countries.

The potential difficulty with creating an all-Australian workforce is the deficit in draftsmen and engineers with submarine experience. There are, and should be in the time frame for the Future Submarine programme, many draftsmen and engineers available in Australia, but we estimate that very few will have relevant submarine experience, and those with submarine experience will be needed to support the *Collins* class or other naval programmes. Any new additions to the design workforce will require some training and time to reach fully proficient status.

The second alternative—creating a submarine design workforce from a mix of Australian and international draftsmen and engineers—offers the opportunity of adding submarine-experienced personnel to the core Australian design workforce when they are needed. There may be a slight decrement in proficiency due to relocation and the integration into a new design environment, but experienced international draftsmen and engineers could reduce the total hours and time to complete the design.[2]

Infusing international personnel could be accomplished in several ways. For example, the design contractor could recruit submarine-experienced personnel on an international scale. Or, companies with offices and workforce in Australia could reach back for personnel in their international offices. Finally, the design contractor could partner with a company of another nation in developing the design. Even this last option, collaboration, could take several forms.

However, international personnel may not be readily available. The United States and the UK, the two countries with large submarine design resources, will both have new submarine design programmes going on during the same time as the Future Submarine programme design effort. Companies in those countries may not have excess capacity to provide resources to Australia. Establishing relationships and commitments early in the programme is necessary if reach-back and collaboration are desired options.

Government Options

The Government has three options to meet the demand for technical personnel resulting from the Future Submarine programme:

- Drawing personnel entirely from the *Collins* class or other existing maritime programmes

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[2] Not all international personnel would need to relocate to Australia. Modern communications and software could provide a virtual design environment in which personnel could be widely dispersed. Electric Boat personnel in the United States successfully supported the *Astute*-class design programme in the UK.

- Hiring entirely new personnel to support the Future Submarine programme and developing their expertise organically through the Future Submarine programme
- A “hybrid” option wherein the Government draws a core of experienced engineers from the *Collins* class or other maritime programmes, and the remainder of the workforce is hired and trained by this core.

We evaluate the various industry and Government options in the next chapter.

CHAPTER ELEVEN

Evaluating Options for Closing the Industry-Specific Skilled Design Personnel Gap

In this chapter, we evaluate the two options open to industry to close the gap in skilled design personnel that we described in Chapter Ten: expanding the submarine design workforce with only Australian personnel or infusing new personnel from other countries.

We begin by describing the model that we used to predict the effects of increasing the size of the submarine design workforce. RAND has used this model in other industrial-base investigations, and we tailored it to Australian circumstances for this analysis. We then go on to discuss our evaluations of the two options open to industry based on outputs of that model.

At the outset, it should be noted that the Future Submarine design effort needs to leverage a technical workforce of sufficient depth and experience that the programme can successfully meet both cost and schedule objectives. Not only will the programme require a certain number of draftsmen and engineers, those workers must also have the appropriate submarine design skills and backgrounds. If too few workers are available, design work will not be done in an efficient sequence—leading to schedule delays and increased cost. Similarly, a lack of experienced workers will result in additional rework or errors that will also cause similar execution problems. Therefore, the Future

Submarine programme must devise an execution strategy in which workforce issues are considered.[1]

RAND's Past Analyses of Gaps

In recent years, RAND has examined the implications of work gaps in defence weapons system procurement (i.e., when production of a weapons system is stopped and then later restarted). In a 1993 study, Birkler et al. summarised the restart experience for 11 aircraft programmes.[2] They found that the first-unit hours after restart were less than the first-unit hours for the initial production run but higher than the hours for the last unit before production stopped (so-called "loss of learning"). In a study the following year, Birkler et al. examined the cost, schedule, and force structure implications of gapping production of nuclear submarines for several years.[3] They concluded that a gap of a few years would increase production costs by billions of dollars. Similarly, in 1998 Birkler et al. examined the timing of the start of production for the CVN 77 aircraft carrier.[4] They found that an earlier-than-planned

1 Quality and safety issues must be considered as well. These issues are not addressed in this chapter, but they should also correspond to the level of workforce experience. That is, an experienced workforce should have fewer of these problems relative to an inexperienced one.

2 John Birkler, Joseph P. Large, Giles K. Smith, and Fred Timson, *Reconstituting a Production Capability: Past Experience, Restart Criteria and Suggested Policies*, Santa Monica, Calif.: RAND Corporation, MR-273-ACQ, 1993.

3 John Birkler, John F. Schank, Giles K. Smith, Fred Timson, James Chiesa, Marc Goldberg, Michael Mattock, and Malcolm MacKinnon, *The U.S. Submarine Production Base: An Analysis of Cost, Schedule, and Risk for Selected Force Structures*, Santa Monica, Calif.: RAND Corporation, MR-456-OSD, 1994.

4 John Birkler, Michael Mattock, John F. Schank, Giles K. Smith, Fred Timson, James Chiesa, Bruce Woodyard, Malcolm MacKinnon, and Denis Rushworth, *The U.S. Aircraft*

start of the CVN 77 would be more cost-effective because it minimised a significant workload drop at Newport Naval Shipyard. In 2001, Younossi et al. examined the costs of a gap in E-2C aircraft production.[5] They found that a gap of four years would lead to an additional US $50 million (then-year dollars) of added cost once production restarted. In 2007, Schank et al. found that sustaining a technical workforce of 800 draftsmen and engineers could result in over US $500 million (then-year dollars) in reduced cost for a follow-on design effort.[6] For all these studies, a gap in production and subsequent restart held significant financial consequences.

This previous research showed that lack of experience increased the cost and schedule of programs—even when a firm had significant prior experience and had maintained skilled workers on other programs. The concern for establishing a new capability is whether the workforce is available and sufficiently skilled. So, the principles are similar. Lack of a sufficient technical workforce will cause delays and cost increases for the programme. These issues are almost certainly magnified when a new capability is to be established.

Although designing a new submarine has similarities to work gap issues, there are also some important differences. One area in which there might be greater impact would be the skill and knowledge gained through actual work. Some technical specialties take decades to develop. Therefore, the lack of a skilled design and engineering workforce due to a gap (and its reconstitution with inexperienced workers)

Carrier Industrial Base: Force Structure, Cost, Schedule, and Technology Issues for CVN 77, Santa Monica, Calif.: RAND Corporation, MR-948-NAVY/OSD, 1998.

5 Obaid Younossi, Mark V. Arena, Cynthia R. Cook, John C. Graser, Jon Grossman, and Mark Lorell, *The E-2C Industrial Base: Implications of a Production Hiatus*, Santa Monica, Calif.: RAND Corporation, DB-328-NAVY, 2001.

6 Schank et al., 2007.

might be far less challenging than establishing a new capability. With such a gap, there will likely be a core set of workers to draw on that can be used to train new workers. When establishing a new capability, the core of workers that serves as the training base does not exist. Firms and government will not have had programs to develop these highly skilled workers. In addition, the resource pool of workers—particularly in the high-end technical specialties—is limited. One does not easily hire someone with several years of submarine design experience. Further, most of the current domestic experience will be in the support rather than new-design phase. Supporting an existing design takes a slightly different mix of skills and does not exercise skills in ways that are needed for a new design.[7]

The workforce in the naval design and engineering industry is in continual flux. The ebb and flow of work and programmes cause changes in demand over time. If demand increases, industry expands the workforce to meet that demand—although its response might be somewhat delayed. If the demand declines, industry shrinks the workforce through staff reductions. Other changes to the workforce also occur. Workers retire and leave the workforce. New workers are hired and trained as needed. Existing workers become more experienced as they apply and utilise their skills. Thus, the design and engineering workforce is a dynamic system that primarily responds to the time-dependent demands placed on it. Its ability to respond to these demands is constrained by a number of factors: labor availability, worker training and absorption practices, worker productivity, and workforce demographics.

[7] See Schank et al., 2007, for a further discussion of this point.

RAND's Technical-Workforce Simulation Model

RAND has developed a technical workforce simulation model to simulate the response to demand described above.[8] The simulation is a time-step model that changes the workforce (employment) levels in response to demand and other inputs. The response to that demand is constrained in several ways (e.g., by the ability to train and mentor new workers). The simulation processes the flow of workers (both gains and losses) with each time step. Workers can be gained through only one way—new hires. However, workers can be lost through a variety of other mechanisms: retirement, attrition (not related to retirement), or layoffs. Furthermore, workers progress through the experience level for each year employed. With each time step, the simulation keeps track of both the work accomplished and the work planned. If less work is accomplished than planned, this work becomes part of the backlog that is added to the next time step. Such a backlog might result from either a lack of available workers or workers with low levels of experience (they perform at a lower productivity level).

Modifying the Model for Australian Circumstances

For this analysis, we modified the model to reflect key differences for Australian industry:

- We added a pool of experienced submarine workers that industry can use, as an alternative to hiring inexperienced workers. The size of this pool was described in Chapter Seven.
- We ignored retirement losses because the average age of the workforce was quite low (about 40 years).

[8] Those seeking more specifics on the model to better understand how changes in demand alters the labor workforce and consequently affects cost and schedule should see Schank et al., 2007.

- Given the large uncertainty in the workload estimates, we modelled the workforce at the total draftsman and engineer level. This aggregation also allows us to reflect the greater level of multiskilled workers in Australia compared with the United States.
- We used a yearly time step, which was the best resolution in the demand that we could generate.
- We allowed some overtime—up to 10 percent.

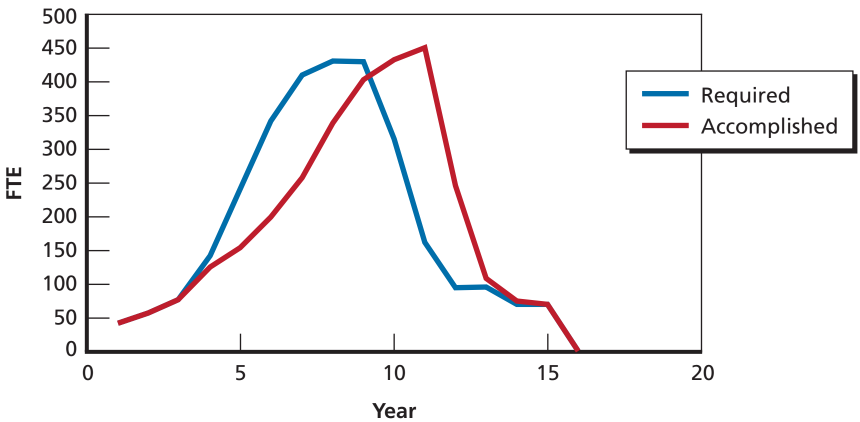
What the Model Can Produce: Required Versus Accomplished Workload

To better understand the output of the workforce simulation model, it is instructive to examine the detailed output from one specific case. As stated earlier, the model tracks (year-by-year) the workforce changes that occur in response to the demand. This workload demand is the amount of work that one plans to finish. We call this workload the required workload. However, given the limitations of expanding the workforce or the skill of the workforce, the work completed in any given year might fall short of that required. We call the work actually done the work accomplished. Figure 11.1 shows example output from the model for draftsmen for both the accomplished and required work.[9] The total design period is 15 years.

Figure 11.1 shows that the required and accomplished work match until the fourth year of the design effort. At this year, the accomplished workload begins to lag behind the required workload. At this point, the pool of experienced submarine workers is exhausted and new hiring cannot keep up with demand. The lag persists until about the ninth year. At this point, the required workload falls off and the workforce can catch up with the backlog. At the very end of the profile, the required

[9] The curve shown is for draftsmen with a total workload of 20 MMH, based on 50 percent of the draftsmen with submarine experience being available.

Figure 11.1
Example Required Versus Accomplished Workload Model Results



RAND *MG1033-11.1*

and accomplished workload match. So, one can see visually how work lags behind what is desired—leading to a schedule slip. One should not infer that there is no delay in the programme just because both profiles reach the same point by year 15. The critical point is the peak of the workload profile. After the peak, the demand drops rapidly—that is the point at which production typically begins. We measure the schedule slip by the shift in the peak workload. We measure increased number of hours as the difference in area between the two curves.

Model Assumptions

We made a number of other assumptions about the Australian technical and design workforce for the model. As discussed earlier, we started with a skilled, fully proficient industry workforce pool of 206 draftsmen and 275 engineers. However, because of the uncertainty in the future demand for these personnel, we varied the fraction of those workers available for the new submarine programme. In addition, new hires beyond this pool have a mix of relevant submarine experience. Half of the workers were new to the field. The rest of the new hires were evenly split between one and two years of experience. These workers represent technical workers who might have naval or maritime experience but no submarine-specific experience. Productivity was assumed to improve over five years. Table 11.1 shows the specific experience distribution for new hires and their corresponding productivity.

We also assumed that the mentoring ratio was three to one—three new employees per experienced worker. The attrition losses were fixed at 3 percent. The maximum growth rate was 35 percent. (That is, the workforce can increase by, at most, 35 percent each year.) These values were informed by both the company surveys and our prior work on technical workforce issues.[10] We assumed a baseline time of 15 years to complete the design.

Table 11.1
New-Hire Experience Levels and Productivity

Year of Employment	Productivity (%)	New-Hire Proportion (%)
1	30	50
2	60	25
3	80	25
4	90	0
5+	100	0

[10] Schank et al., 2007.

Forecasting the Future Submarine Programme Workload: How Large a Skilled Design Workforce Will Australia Need?

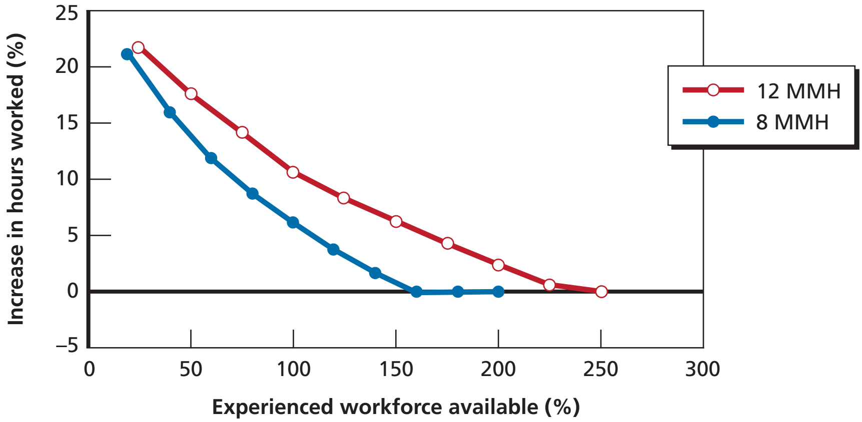
We employed the model to quantitatively gauge the size of the skilled design workforce that Australia will need to handle expected demand from the Future Submarine programme. Specifically, we used the model to forecast the size of the skilled workforce (which we considered as a percentage of today's pool of draftsmen and engineers) that would be required to design the Future Submarine within the design effort range of 8–12 MMH that we discussed in Chapter Three. We also predicted the size of the workforce that would be required to design the submarine on two different schedules: a 15-year profile and a 20-year profile.

The Future Submarine Will Require More Work Hours Than the Anticipated Available Skilled Workforce Can Provide[11]

Figure 11.2 shows the increased work hours for the Future Submarine programme versus the percentage of the experienced draftsmen available. Two planned total workloads are shown: 8 MMH and 12 MMH. The design time line is 15 years. Notice that it takes increasingly more hours to complete the design as the percentage of available experienced personnel declines. Anticipating that somewhere between 20 and 40 percent of the skilled draftsmen will be available for an in-country–only approach, the programme can expect work hours to increase 16–21 percent for the planned 8 MMH and 17–22 percent for 12 MMH. To have no growth in the work hours, somewhere between

[11] Rather than cost, we explore the changes in the number of work hours to complete the design. These changes in hours should track with cost, but we have not fully accounted for cost differences. One would need more detailed financial data from the firms to assess costs fully.

Figure 11.2
Increased Draftsman Hours Versus Skilled Workforce Available, 15-Year Design Profile



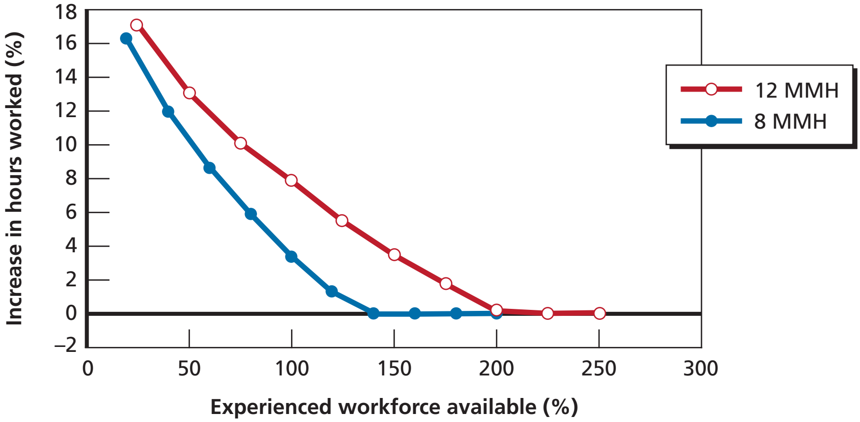
RAND *MG1033-11.2*

150 and 225 percent of the skilled workforce would need to be available—more than currently exist in Australia.

Figure 11.3 shows a similar trend for the engineering workforce. Here the growth in hours can be anticipated to be about 12–17 percent for both 8 MMH and 12 MMH with 20–40 percent of the experienced labor pool available. Between 150 and 200 percent of the engineers with submarine experience would need to be available to result in no growth in hours.

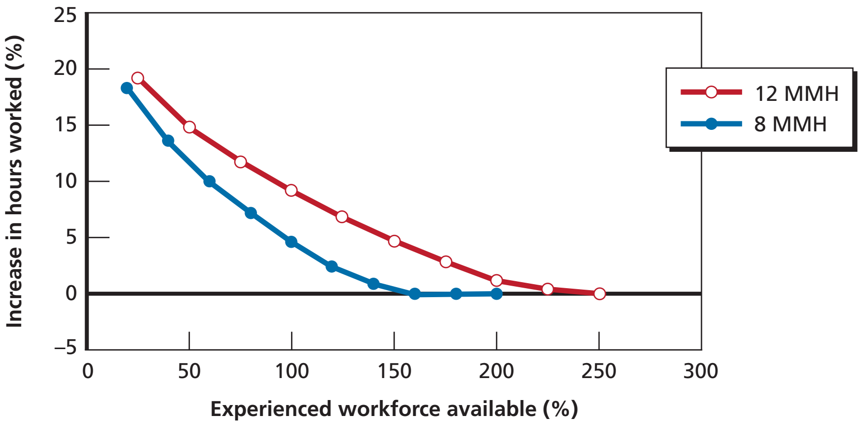
Figure 11.4 combines the growth in hours for both draftsmen and engineers. The component curves shown in Figures 11.2 and 11.3 were weighted based on their proportion of the total workload. Again, about 14–18 percent growth can be expected when only 20–40 percent of the workforce with submarine experience is available. As on the previous figures, more workers than currently exist would be needed to avoid any growth in hours.

Figure 11.3
Increased Engineering Hours Versus Skilled Workforce Available, 15-Year Design Profile



RAND *MG1033-11.3*

Figure 11.4
Increased Technical Hours Versus Skilled Workforce Available, 15-Year Design Profile



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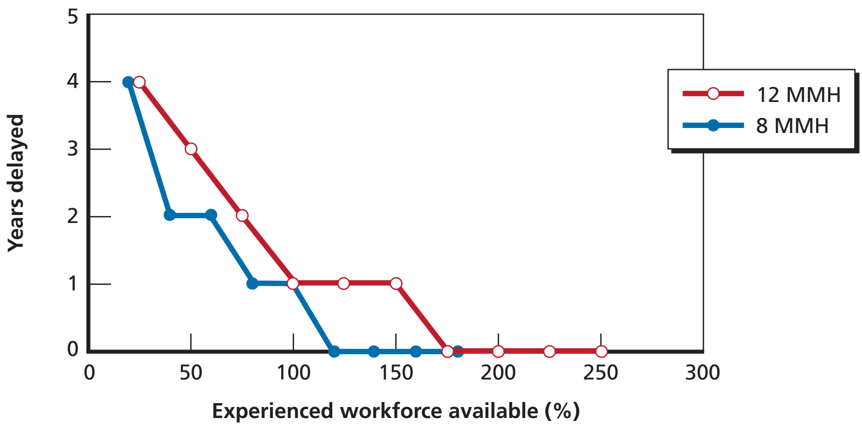
The 15-Year Design Schedule Will Encounter Schedule Delays, Based on Anticipated Skilled Workforce Availability

The trends for schedule delay are similar to those for the growth in hours—the fewer skilled workers there are, the greater the schedule delay. Figure 11.5 shows the schedule delay related to draftsmen for 8 MMH and 12 MMH. Notice the steep slope at lower numbers of experienced personnel. The schedule delay is very sensitive—even a few percentage points of change can increase the schedule delay dramatically. Recall that the time steps are yearly. Thus, the lowest resolution is plus or minus one year. If we had modelled with a smaller time step, the curves would be smoother and would not show "steps" as does Figure 11.5. Nonetheless, a lack of experienced draftsmen might cause schedule delays of two to four years if only 20–40 percent of the skilled draftsmen were available. It would take between 125 and 175 percent

Figure 11.5
Schedule Delay Versus Skilled Draftsman Workforce Available, 15-Year Design Profile



RAND *MG1033-11.5*

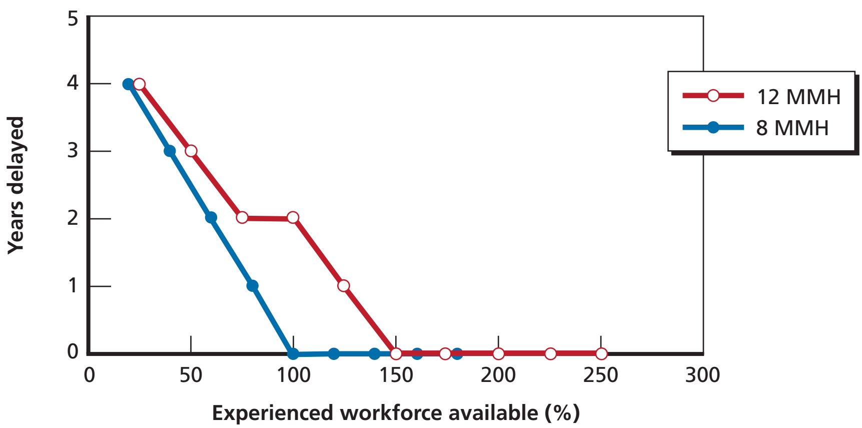
of the skilled draftsmen to avoid a delay (depending on the total workload).

Figure 11.6 shows the schedule delay for the engineer workload. It is similar to that for draftsmen. Although we do not model the interaction between draftsmen and engineers, we can approximate the overall schedule delay as being the maximum of either draftsmen or engineers. For this specific analysis, the engineering work drives the schedule—so the overall schedule delay would look identical to Figure 11.5.

The 20-Year Design Schedule Will Encounter Fewer Schedule Delays Than the 15-Year Schedule, Based on Anticipated Skilled Workforce Availabilities

As we have seen, the Australian technical workforce will have difficulty meeting the demands for the Future Submarine programme

Figure 11.6
Schedule Delay Versus Skilled Engineering Workforce Available, 15-Year Design Profile

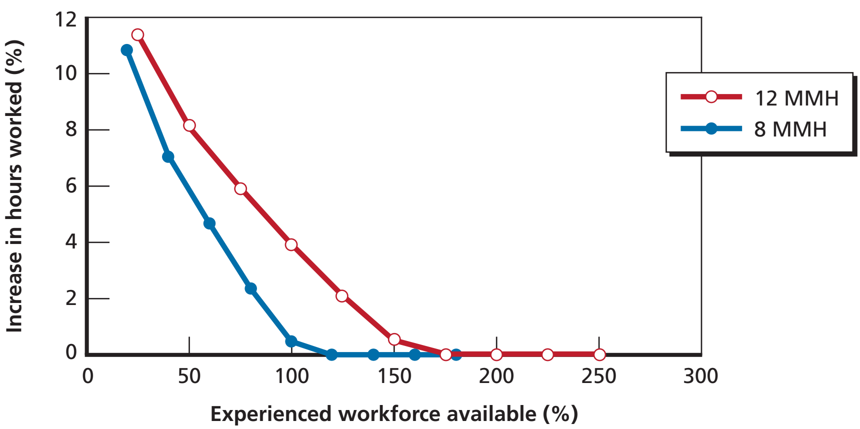


RAND *MG1033-11.6*

with the existing skilled workforce. One option would be to lower the peak demand by extending the design period. Figure 11.7 shows the increase in work hours for both draftsmen and engineers for a 20-year design effort. Note that the additional hours are much fewer than in Figure 11.4. The expected increase is 7–11 percent (rather than 14–18 percent). So extending the design schedule by five years nearly halves the increase in workforce hours when 20–40 percent of the experienced workforce is available. Figure 11.8 shows the schedule delay for a 20-year profile. Once the workforce available rises to 40–75 percent, there are no schedule delays. Thus, a 20-year design duration helps to mitigate many of the problems seen with a 15-year duration.

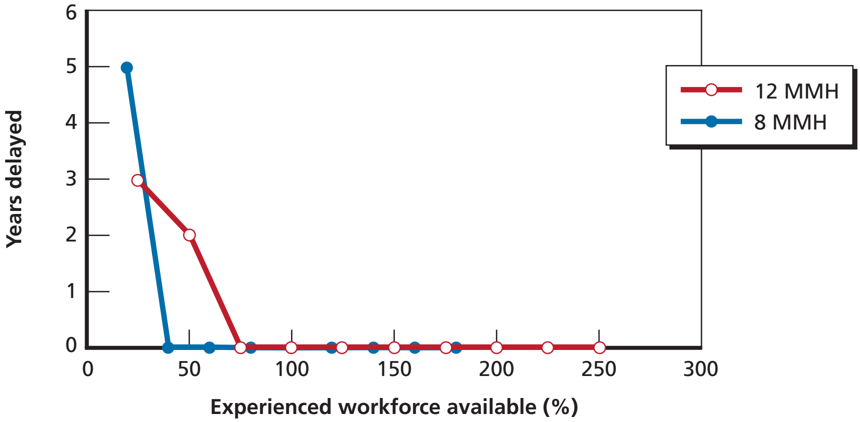
While extending the design duration can result in a smaller penalty for a less than fully proficient design workforce, designing the 12 submarines of the new class in flights will not necessarily have the

Figure 11.7
Increased Technical Hours Versus Skilled Workforce Available, 20-Year Design Profile



RAND *MG1033-11.7*

Figure 11.8
Schedule Delay Versus Skilled Workforce Available, 20-Year Design Profile



RAND *MG1033-11.8*

same impact. As mentioned, we assume the first "flight" would involve basically a new submarine design and will drive the peak demand for design resources. Subsequent flights will be evolutions of the first flight and would have lower peak demands. Although designing in flights may not help with the immediate problem, it could help sustain a capability edge in the region as well as the capability to build and support the new submarines and sustain a new submarine design capability.

Quantitative Conclusion: Industry Skilled Workforce Will Fall Far Short of Programme Demand

Recall from our analyses in earlier chapters that we estimated the peak demand for industry personnel who would be needed for a new submarine design programme to range from approximately 600 draftsmen and engineers (for a total design workload of 8 MMH) to 900 (for a total design workload of 12 MMH).

However, all submarine-experienced personnel in Australia currently support existing programmes. Based on our analysis of limited data, we project there may be only 100 to 200 submarine-experienced draftsmen and engineers available to support a new submarine design.

Thus, there is a significant gap in experienced industry personnel if the Future Submarine programme elects to develop a new design solely in Australia. Also, new personnel would have to be hired and trained to replace any experienced personnel who move from existing programmes to the new submarine design effort.

Summary Observations: Evaluating Options Available to Industry

Using the workforce model described above to understand the implications of the size of the experienced workforce on the hours to complete the design (a proxy for cost) and schedule, we found that hours can be anticipated to grow 14–18 percent when 20–40 percent of the experienced workforce is available. There are too few workers with experience to meet the peak demands. Similarly, the schedule increases two to four years for the same available workforce assumptions. Extending the planned design schedule to 20 years (and holding required man-hours constant) halves the growth in hours (7–11 percent) and reduces the schedule delay to one to two years. These findings have implications for the two options available to industry.

Option 1: Build from Within Australia

The analysis above suggests that hiring personnel from within Australia to build the platform design team for the new submarine would add significantly to cost and time. This is due to the relatively small core of submarine-proficient personnel currently in Australia. Although there may be numerous draftsmen and engineers available in-country if the demands of other naval programmes and commercial markets decrease in the future, these draftsmen and engineers have little or no submarine-related experience and would require experience in the field and training that leads to the increase cost and schedule.

The advantage of this option for closing the gap is that it builds a national capability that could provide long-term stability in submarine design resources without dependence on other countries. A potential disadvantage is reducing the workforce after the peak demand is reached. Where do the trained personnel go when the new-submarine design effort begins to decline? It may be difficult to attract the technical personnel to support other Australian industries if they do not see a long-term demand for their skills.

When weighing the options for closing the gap in submarine design resources, the desired future sustained level of submarine-proficient technical personnel must be considered. Draftsmen and engineers and will be needed to provide maintenance and modernisation support for the new submarine once it enters service. And a new submarine design may be required sometime in the future. Furthermore, submarine-proficient draftsmen and engineers could contribute to future surface ship design efforts.

Option 2: Infuse International Experienced Personnel

The above analysis suggests that increasing the number of submarine-proficient personnel above those currently available in Australia can reduce cost and schedule delays. For example, if the total demand is 8 MMHs, adding approximately 100 draftsmen and 140 engineers with submarine design experience could potentially eliminate any cost or schedule growth if the 500 submarine-experienced draftsmen and engineers in Australia were available to support the Future Submarine programme. These numbers increase to approximately 260 draftsmen and 280 engineers if the total demand is 12 MMHs. Of course, if fewer than the 500 experienced people were available, more international experience is needed to eliminate any cost or schedule growth.

These additional submarine-experienced personnel must come from outside Australia. Infusing these international experienced personnel could take several forms:

- The main design company could recruit international submarine-experienced personnel.
- Companies such as BAE and BMT could transfer submarine-experienced personnel from their offices in other countries.
- The main design company could collaborate with a company in another country on the design of the new submarine (assuming that intellectual property and/or technology transfer restrictions could be overcome).

These options may make it easier to draw down the workforce after the peak demand period. The international personnel could return to their home countries to continue submarine designs. However, key personnel may see this future downturn, or may be required in their home country, and so leave the project early. Also, the United States and the UK have new submarine design efforts (replacements of their current ballistic missile submarines) that overlap the Future Submarine programme, limiting the availability of skilled personnel. But the infusion of international personnel may be the only option for certain skills that are in very short supply within Australia.

Collaboration with a company in another country could take different forms. For example, the design of a complete section of the submarine could be assigned to another company. For example, the forward compartment of the U.S. *Seawolf* was designed by Newport News and the propulsion plant and engine room were designed by EB.

Also, the United States and the UK are collaborating on the design of a common missile compartment for the UK *Successor* programme and the U.S. *Ohio* Replacement Program. Another alternative is to assign the engineering responsibility for a selected distributed system to another company with the drawings developed in Australia. Subcontracting some of the more complicated analysis and engineering reduces technical risk and, therefore, the likely associated costs. This alternative was used in the U.S. *Seawolf* programme, where Newport News was responsible for much of the fluid systems engineering definition and EB produced the piping construction drawings. The disadvantage of a collaboration option is that Australia may not develop a full design capability.

Any collaborative effort must initially set guidelines and agreements on responsibilities, accountability, oversight, work share, and profit share. We assume the desired goal is overall management by an Australian entity that subcontracts to an international company.

The ability to infuse international submarine experience may be limited. Both the United States and the UK will be engaged in new submarine designs during the same time as the Future Submarine programme. Companies in those countries may not have excess capacity to share with Australia. If reach-back or collaboration is a desired goal, interactions and commitments should be established early so that all countries and companies can shape their perspective workforces.

CHAPTER TWELVE

Evaluating Options for Closing the Government-Specific Personnel Gap

The Future Submarine effort requires an experienced Government workforce large enough and with enough expertise across a variety of disciplines to support the design process. If there are too few engineers, the Government may not be able to provide sufficient input to and oversight of the design process. As a result, the design work could be delayed as industry waits for Government approval of design products or the Government may not perform its due diligence in exercising technical authority. Similarly, a lack of experienced engineers with the appropriate expertise will result in a lack of effective oversight. In some technical areas, the Government currently provides a dominant share of the expertise. Therefore, the Future Submarine programme must devise a strategy for its Government workforce that provides a robust design oversight capability. In this section, we explore how the available Government workforce can meet its objectives.

The Government has three options to meet the demand for technical personnel resulting from the Future Submarine programme. In the first option, it draws personnel entirely from the *Collins* class or other existing maritime programmes. In the second option, it hires entirely new personnel and develops their expertise organically through the

Future Submarine programme. In the third, hybrid option, it draws a core of experienced engineers from the *Collins* or other maritime programmes, and the remainder of the workforce is hired and trained by this core. As discussed previously, our analysis counts the Government and external service providers equally.

Option 1: Draw Personnel from the *Collins* Class or Other Maritime Programmes

Notwithstanding gaps in several important skill categories, the existing workforce has several features that make it attractive to the Government when planning to design a new submarine. First, the workforce has significant submarine experience by virtue of having worked on the *Collins*-class programme. Even if Australia were to pursue an entirely new design, individuals with experience on the *Collins* class are in a position to leverage lessons learned for the Future Submarine. This experience may translate to improved technical oversight and provide efficiencies in approving design products. Second, existing personnel are familiar with the procurement and other processes that are an inherent part of working at DMO and for the Government. Although familiarity with Government processes could be gained on the job, using existing personnel to meet the demand for technical personnel would avoid the start-up costs associated with training new personnel. In short, staffing the Future Submarine programme with existing personnel would leverage experience gained through the *Collins* class and avoid costs associated with hiring and training new staff.

Using the existing workforce to support the Future Submarine programme necessarily draws resources away from the programmes the workforce currently supports, and a decision to do so must account for risks to those programmes. A thorough analysis of the demand for technical personnel across DMO and DSTO is beyond the scope of the study. However, the in-service support schedule for the *Collins* class provides some data about the future demand for existing personnel.

The *Collins* class in-service support requirement will continue until the last submarine is decommissioned. The workload is unlikely to decrease before decommissionings begin and may actually increase as the *Collins* class grows older. Thus, assuming that decommissions of *Collins*-class submarines begin after 2025, DSME, the Collins Program Office, and SMCSPO will likely need to maintain personnel at levels comparable to the present throughout the design of the new submarine simply to support the *Collins* class.

Of course, the SMCSPO supports a continuously updating programme and will likely be available for inclusion in the Future Submarine project. As a result, there may be opportunities to leverage combat system personnel across programmes. Scientists and engineers at DSTO may be available on an earlier schedule, as *Collins*-class in-service support decreases and allows DSTO attention to focus more on fundamental science and technology issues. However, as a science and technology organisation, DSTO cannot be expected to provide the sort of engineering capability provided by programme offices and DSME.

Option 2: Hire New Personnel

A second option for meeting the Future Submarine demand for technical personnel is to hire an entirely new workforce. This option naturally avoids the risk associated with drawing personnel away from supporting the *Collins* class and other programs. However, it fails to leverage the considerable knowledge base that has accumulated as a result of the *Collins* class and is likely to be the most expensive in terms of training. These disadvantages may translate to delays in design process and failure to fully apply lessons from the *Collins* class. The likely outcome of this option is that the Government will be unable to carry out its responsibilities efficiently, leading to an increased risk of cost escalation and schedule delay. Thus, although this option is the logical antithesis of drawing from existing personnel, it nonetheless has significant drawbacks.

Option 3: Draw Core Personnel from the *Collins* Class to Start the Programme, Then Grow New Personnel

A natural hybrid strategy is to draw a core workforce from those working on the *Collins* class or other maritime programmes and to hire new personnel both as replacements for the core and to fill out the Future Submarine programme. Assuming a sufficiently experienced workforce is left to service the *Collins* class and other programmes, this option would gain the benefits of drawing from the *Collins* class experience, reduce the risk of under-resourcing other programmes, and likely incur reasonable costs in training.

Natural questions include how many personnel should form the core and how the core staff should be chosen. An analysis of risks and benefits at this level of detail is beyond the scope of this research. However, the supply of Government technical personnel is sufficiently large relative to what we estimate is needed that this option appears feasible.

Choosing Amongst the Government Options

Thus, there are three logical options for closing the personnel gap in the Government. Clearly, the best option is to draw a core of technical personnel from the *Collins* class and other maritime programmes and to hire additional personnel both as replacements for the core and to fill out the Future Submarine programme. This option would provide the benefit of drawing from the *Collins* class experience, reduce the risk of under-resourcing the *Collins* class and other programmes, and likely incur reasonable training costs.

CHAPTER THIRTEEN

Evaluating Options for Closing Skill Gaps That Exist Across Industry, Government, and Academia

In this chapter, we focus on closing potential gaps in engineering skills and technology that exist across industry and Government. We do so by evaluating skill sets and facilities for industry, Government, and academia in total, looking at three functional technology areas that are relevant to a submarine design: combat systems, hull form design, and internal HM&E systems. For all three areas, we discuss the size of the gap and potential solutions.

Although there are numerous approaches to closing a skill gap, this analysis focuses on two methods. First, Australian industry and Government organisations could partner with institutions in allied countries to leverage a larger technical base. Examples of such a partnership include the current RAN–U.S. Navy collaboration on submarine fire control systems and the arrangement between the Australian Submarine Corporation and Kockums during the design and production of the *Collins* class. Second, Australia could start a dedicated domestic development effort to provide the required personnel and technology. This option may become necessary if allied institutions are unable or unwilling to share technology.

Combat System Gap

In the area of combat systems, our gap analysis suggested that industry and Government have sufficient numbers of engineers with the applicable technical and management skills, as well as a sizeable facility base to support future design. In addition, both industry and Government could take advantage of potential partners in allied countries.

The RAN currently participates in a vigorous ongoing collaboration with the U.S. Navy to field and continuously upgrade a modern submarine command decision data-management and weapons-control system, the AN/BYG-1. As a result, the RAN is able to leverage its investments and gain access to a larger community of submarine combat system expertise. Of course, the U.S. Navy supports nuclear submarines and the RAN must manage any differences that emerge. The Future Submarine project may be able to expand this collaboration depending on its choices of sonar systems.

The U.S. Navy and its engineering organisations, primarily the Naval Undersea Warfare Center in this case, have a similar programme of continuous sonar-system upgrades, the AN/BQQ-10 Acoustic Rapid Commercial Off-the-Shelf Insertion (ARCI) programme. The RAN, through SMCSPO and DSTO, may be able to participate in this programme. Between its current investments in evolving the *Collins*-class combat system as part of its collaboration with the U.S. Navy, its relatively large number of engineers actively involved in submarine combat system development, and its significant facilities, it appears that any potential gaps in combat systems can easily be overcome if the teaming arrangement with the U.S. Navy continues. However, such an arrangement will likely preclude involvement by non-U.S. firms.

Hull Form Design Gap

In the area of hull form design, the investments made in Government and academic expertise have resulted in a core group capable of supporting a new submarine design. However, there is a large difference between individual research projects or engineering modifications to the *Collins* class and being responsible for the design of a hull form on a new submarine. As in the case of combat systems, it is likely that Government organisations will be able to take advantage of partnerships with allied governments. For example, DSTO has an ongoing relationship with the U.S. Naval Surface Warfare Center at Carderock in the area of hydrodynamics and naval architecture.

In addition, DSTO has science and technology collaborations with Canada, the UK, and Holland. The ability to leverage these relationships allows Australia to potentially access facilities that it may not otherwise be able to utilise. Example facilities that could be useful to a successful design include the U.S. Navy's Large Cavitation Channel and Large Scale Vessel testing regime. On the industry side, most modern submarine designers have significant experience and facilities to support hull form design. The lead Australian industrial designer can look to ally itself with submarine designers in allied countries.

In the case of hull forms, there is no reason to distinguish between a diesel-electric and a nuclear submarine designer. Therefore, submarine designers in the United States and the UK could provide assistance. Relative to combat systems, there is more cause for concern in the area of hull form design. However, there are reasonable numbers of engineers with submarine experience who can be supplemented with personnel and facilities in allied countries.

Internal HM&E Systems Gap

In contrast, HM&E design appears likely to present a significant capability gap for a domestic design that is more difficult to mitigate. Unlike combat systems and hull form designs, there are fewer possibilities for collaboration with allied government and industrial organisations.

In the United States and the UK, government and industry submarine designers exclusively design nuclear submarines. As a result, they can potentially provide assistance in the area of hull forms and do actively collaborate with Australia in the area of combat systems. However, because each country focuses on nuclear submarine design, neither can provide significant assistance in the area of non-nuclear propulsion and energy.

In addition, the Future Submarine operating requirements articulated in *the Defence White Paper 2009* exceed the propulsion capabilities of the production diesel submarine of any potential allied partner. Australia's submarine community—Government and industry—will have to solve this capability gap on its own.

To mitigate its technical risks in this area, Australia can take several steps. First, it must make a long-term dedicated effort to develop the required technology and expertise. Second, a land-based test facility can be a critical element in the development effort. This land-based facility would include and integrate all elements of the propulsion and energy systems—diesel generators, propulsion motor, energy storage (batteries and, if selected, an AIP system), electrical transmission, and control. To maximise its development value, this facility would mimic at-sea conditions to the greatest extent possible. As such, it would include a water brake system on the propulsion motor to run the system through expected operations. It would also provide the ability to operate the diesel generator with an induction mast to artificially mimic the induction pressure drops and interruptions. Additionally, the facility will need to create the variable back-pressure conditions typical of a snorting diesel submarine.

CHAPTER FOURTEEN

Conclusions and Policy Considerations

As the analysis in the preceding chapters suggests, Australian industry and Government together will need a domestic workforce of roughly 1,000 skilled draftsmen and engineers to create and oversee the design of a new, conventionally powered submarine for the RAN. While technical personnel exist in sufficient, if not large, numbers in Australian industry and Government, we found that a workforce of this size and capabilities does not exist in Australia today.

In Australian industry, relatively few technically proficient personnel have experience in submarine design. And of those who do have the relevant design experience, many may be engaged in work on other current and future programmes, leaving relatively few available to support the design of the Future Submarine. Nevertheless, Australian industry has a core of experienced personnel who could serve as the base upon which to build a new submarine design team.

Similarly, demands from current and future programmes may preclude the Government from having enough technically proficient design personnel available to oversee a new submarine design programme. The Government's design management resources can be characterised as having breadth, but little depth. In some specific skill areas—propulsion, fluids, electrical systems, cost estimation, testing, and production oversight—Government expertise is particularly shallow. Australia also needs an integrated propulsion and energy test facility—the most significant technology advances for the Future Submarine may be in that area.

Despite these shortcomings, industry and Government have options for closing the gaps. Under the right circumstances, Australia could cultivate the 1,000-person design workforce that industry and Government would need over the next 15 to 20 years. However, the Commonwealth could shorten the duration and lessen the costs of designing a new submarine if it were to collaborate with foreign design partners rather than rely exclusively on a domestic workforce to design the vessel.

Closing the Gap in Industry

Our analysis of the demand for technical resources in industry suggests that there may be a peak demand for between 600 and 900 draftsmen and engineers to support a new submarine design programme. We also estimate there may be approximately 500 technical personnel with submarine design experience amongst the companies that could provide resources for a new submarine design. But, because of the continuing need to support the *Collins* class and other naval programmes, few of these submarine-experienced technical personnel may actually be available when a new submarine design team is formed.

Our analysis showed the cost (in additional man-hours) and schedule impacts of starting the new design effort with differently sized pools of submarine-experienced personnel. If 20 percent of the submarine-experienced personnel in Australia were available for the new design effort (about 100 draftsmen and engineers), the total man-hours of the programme would increase by approximately 20 percent and the design schedule would slip by approximately four years. If twice as many submarine-experienced personnel were available (i.e., 40 percent, equal to approximately 200 draftsmen and engineers), total man-hours would increase by approximately 15 percent and the schedule would slip by approximately three years. Cost and schedule delays can be avoided only if the current numbers of submarine-experienced personnel in Australia were augmented with between 250–500 submarine-experienced personnel from outside the country.

There are basically two options for closing the gap in industry resources—either hire and train personnel from within Australia or infuse submarine-experienced personnel from outside Australia.

Industry Option 1: Hire and Train Personnel from Within Australia

Building the new submarine design team solely from within Australia requires recruiting and training draftsmen and engineers with no submarine experience. The non-productive man-hours resulting from less-proficient personnel increase the total man-hours and schedule needed to accomplish the design. In addition to the increased cost and schedule, this option also results in the need to draw down the newly trained submarine design cadre as the new design programme nears completion. However, the end result of this option is a total submarine design capability within Australia with little or no reliance on organisations outside the country.

Industry Option 2: Infuse Submarine-Experienced Personnel from Outside Australia

Infusing submarine-experienced personnel from outside Australia reduces the non-productive man-hours associated with training less-proficient personnel and, therefore, reduces cost and schedule growth. Also, the international personnel could return to their home countries as the new design programme winds down. The disadvantage of this option is Australia may not be left with the total capability needed to design a new submarine.

Submarine-experienced draftsmen and engineers could be added to the Australian design team in various ways. The main design firm could recruit on an international basis, or Australian organisations with offices in other countries could draw on those international resources. Also, the main design firm could collaborate with an international company. Such a collaboration could take several forms, including assigning a specific section or a specific system of the new submarine to the international company or just merging people from the other company into the Australian design team.

Infusing international submarine-experienced personnel may be the only alternative for certain skills. Our industry survey suggests there are very few submarine-experienced piping/HVAC and electrical draftsmen in Australia. Other skills with submarine experience in short supply include engineers skilled in fluids, electrical systems, naval architecture, signatures, and programme management. However, submarine design companies in the United States and UK will be involved in new design programmes to replace their country's ballistic missile submarines. Because these demands occur at the same time as the Future Submarine design programme, submarine-experienced personnel from the United States and UK may not be available.

Preferred Approach: A Mixture of Option 1 and Option 2

The preferred approach for building an industry design team for the new submarine programme may be a mixture of the two options. Some level of international submarine-experienced personnel could be added during the first few years of the programme. In addition, draftsmen and engineers from within the country could be recruited and trained to augment the submarine-experienced core. There may be some additional man-hours associated with the non-productivity of the less proficient personnel, but the end result would be a solid core of submarine design experience in country.

Closing the Gap in Government

Broadly speaking, our surveys of and interviews with government organisations suggest that significant and experienced submarine-design personnel resources are available. Across skill categories relevant to submarine design, the most-significant capability resides in combat systems, no doubt reflecting the ongoing *Collins*-class combat-system programme. In contrast, in the area of HM&E, the government appears to have significant breadth but less depth. For example, there are few (if any) government personnel specialising in the areas of propulsion, fluids, electrical systems, cost estimation, testing, and planning and production. However, any analysis of the potential government workforce must reflect the fact that existing personnel are fully employed.

Our analysis clearly shows that the best option to close any gap in the Government's engineering workforce involves drawing a core of technical personnel from support of the *Collins* class and other maritime programmes and hiring additional personnel both as replacements for the core and as a way to fill out the Future Submarine programme. This option would draw from the *Collins* class experience, reduce the risk of under-resourcing the *Collins* class and other programmes, and likely incur reasonable costs in training.

Closing the Skill Gaps Existing Across Industry, Government, and Academia

Our analysis examined three functional technology areas relevant to a submarine design: combat systems, hull form design, and internal HM&E systems. In the area of combat systems, the gap analysis suggested that industry and Government have sufficient numbers of engineers with the applicable technical and management skills, as well as a sizeable facility base, to support future design. In addition, both the industry and government can take advantage of potential partners in allied countries. In the area of hull form design, the investments made in Government and academic expertise has developed a core group capable of supporting a new submarine design. However, there is a large difference between individual research projects or engineering modifications to the *Collins* class and being responsible for the design of a hull form on a new submarine. As in the case of combat systems, it is likely that government organisations will be able to take advantage of partnerships with allied governments.

In contrast, HM&E design appears likely to present a significant domestic design-capability gap that will be more difficult to mitigate. Unlike combat systems and hull form designs, there are fewer possibilities for collaboration with allied government and industrial organisations. Submarine designers, both government and industry, within the United States and the UK have concentrated on nuclear propulsion and energy management issues in recent decades. The degree to which they will be able to assist on non-nuclear propulsion and energy management options is an open question. Australia's submarine community—Government and industry—will have to solve this capability gap on its own. To mitigate its technical risks in this area, Australia can take several steps. First, it must make a long-term dedicated effort to develop the required technology and expertise. Second, it should build an integrated land-based test facility, which is a critical element in the development effort.

Policy Considerations

We found that a base of technical resources, including personnel, software tools, and facilities, exists in Australian industry and Government to support the design of a new submarine. Numerous technical draftsmen and engineers who could contribute to a new submarine design exist in Australian industry. However, only a small number of those technical personnel have experience in submarine design, and many of them may be otherwise engaged to meet the demands from other commercial and naval programmes, including support for the *Collins* class.

These findings lead to several policy considerations:

- Relying on in-country resources exclusively to design the new submarine could increase the total man-hours needed to accomplish the design by approximately 20 percent and lengthen the schedule by three to four years. Nonetheless, senior leaders in the Commonwealth may choose to invest in such technical and managerial expertise.
- Using submarine-experienced personnel from other countries to perform some of the design tasks could result in a smaller increase in man-hours and a shorter schedule. These personnel could be recruited by the platform design firm, come from an Australian platform design concern's overseas offices, or from collaboration between an Australian design company and an international submarine design and construction firm.
- Lengthening the Future Submarine's design schedule from 15 to 20 years while not changing the fully proficient man-hours

required by the design could reduce the peak requirements for skilled personnel. This would reduce the total man-hours needed to accomplish the design and allow needed technologies to mature.

- Designing the Future Submarine in flights would not necessarily have the same effect as lengthening the design period. The first flight would basically involve a "new" submarine design; subsequent flights would have smaller peak demands and could help in sustaining future submarine design capability.
- Developing personnel with programme management skills is important for both industry and Government. Individuals with such skills are needed to lead the Future Submarine programme to a successful conclusion.
- Building an in-country design capability only to let it wane once the design effort is completed might be counter-productive. It is critical that the Australian Defence Force be able to meet technology advances posed by regional adversaries and to adapt to changes in mission priorities. Maintaining such an edge requires a sustained submarine technical capability. Moreover, technical personnel in both industry and Government are needed to conduct and oversee the production programme and to provide in-service support for the new submarine.

APPENDIX A

Operational Safety Considerations

Submarines operate in a hostile environment essentially every time they are submerged. There has traditionally been a strong emphasis on ship safety and survivability in creating a unique subset of design rules that address ship safety.[1] Several sets of design rules exist that may be applied to manned submersibles and dive systems. The majority of countries operating submarines have design requirements and attributes codified to address submarine safety aspects that are generally not available in the open literature. Submarine safety has four major pillars:

1. Establishing design rules and guidance
2. Collecting quality evidence that ensures that the developed design follows prescribed design rules, that verifies that construction processes are in accordance with the design, and that successfully tests the completed systems
3. Verifying and validating that the objective quality evidence is sufficiently robust, broad, and complete to allow for formal certification or classification by an approval agency of the design

[1] These safety issues with respect to design are referred to as SUBSAFE by some countries.

in general and of the specific ship as constructed. The system documentation must be constructed and retained in an auditable manner

4. Codifying the processes so that certifications can be retained after the vessel is delivered.

The Government will need to establish the extent of the submarine safety criteria. Maintaining certification or classification is a significant life-cycle cost. Safety may be limited to the prevention of, and recovery from, flooding, or it may be more extensive, addressing the gamut of safety-related issues—depth excursions, control system failures, fires, atmosphere contaminates, high temperature/pressure fluid systems, etc.

If the Government does not have the required technical acumen, past experience, or desire to develop design rules and process documents, independent third parties with pre-packaged ship design and construction rules are available. Most notably, several of the ship classification societies, American Bureau of Shipbuilding, Bureau Veritas, and others consider this a core business. Germanischer Lloyd (GL), the German ship classification society, has made available design rules for warship submarine design (as opposed to submersible design criteria), construction, testing, and certification available for review. A significant number of submarine ship systems and several whole-ship designs have been classified by Germanischer Lloyd.[2]

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[2] Note that we are not suggesting Germanischer Lloyd; rather, we are identifying independent third parties with available, pre-packaged design and construction rules. The RAN has used GL as an authority to classify (certify) the *Anzac* frigate design, and the South African Navy used GL to classify the Type 209 submarine.

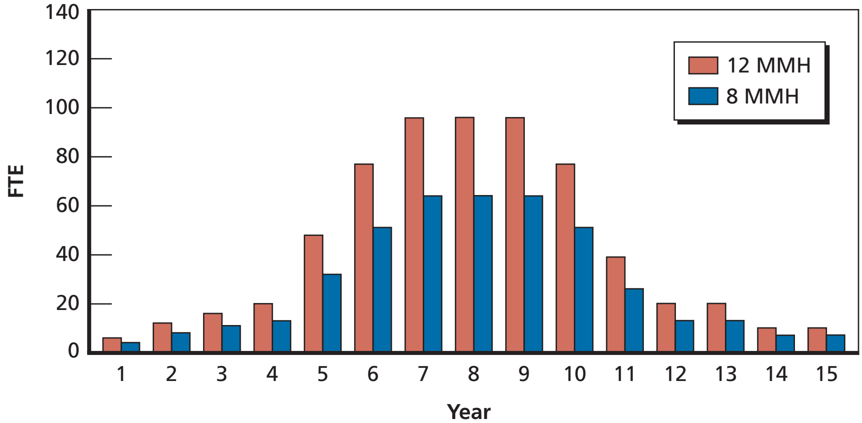
APPENDIX B

Workload Profiles by Skill

This appendix details RAND's estimates of the number of FTE personnel that would be required to design a large, conventional submarine along the lines contemplated by the Commonwealth for the Future Submarine. Each figure displays the workload that would be required at the 8 MMH and 12 MMH total levels of effort for one of the discrete draftsman or engineering skills that we identified in Table 2.1.

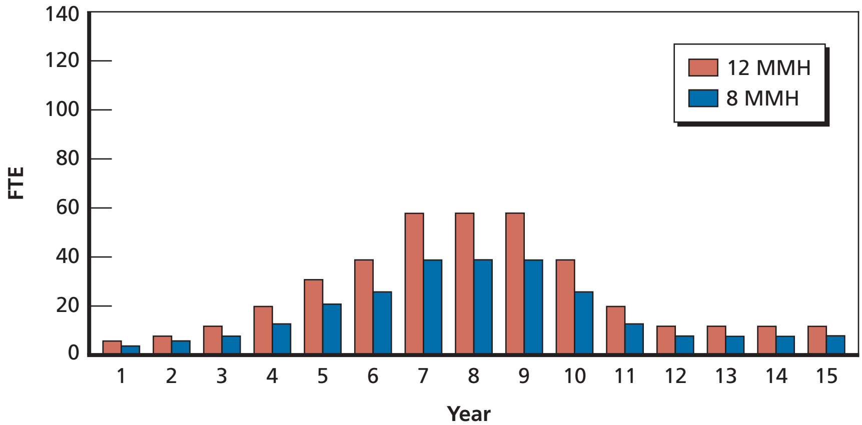
Although the bar charts in the figures give an appearance of precision, readers should be cautioned that they are rough-order-of-magnitude estimates. What is important is not the precise numbers but the relationships and trends that they portray.

Figure B.1
RAND Estimate of FTE Electrical Draftsmen Required by Industry to Design a Large, Conventional Submarine, by Year



RAND *MG1033-B.1*

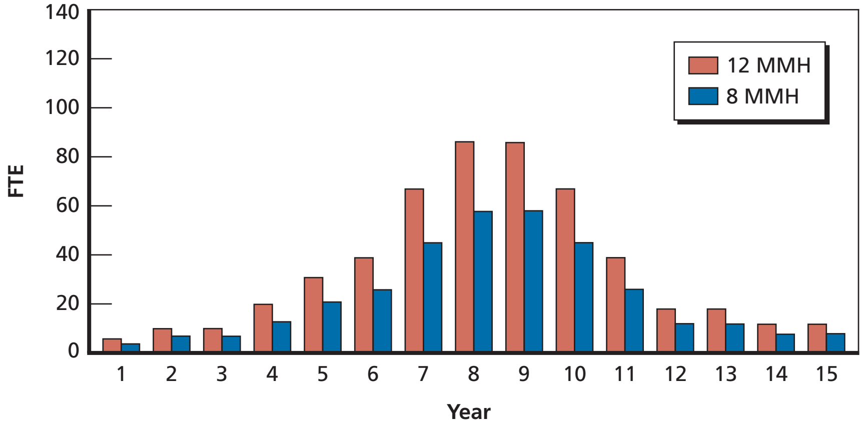
Figure B.2
RAND Estimate of Number of FTE Mechanical Draftsmen Required by Industry to Design a Large, Conventional Submarine, by Year



RAND *MG1033-B.2*

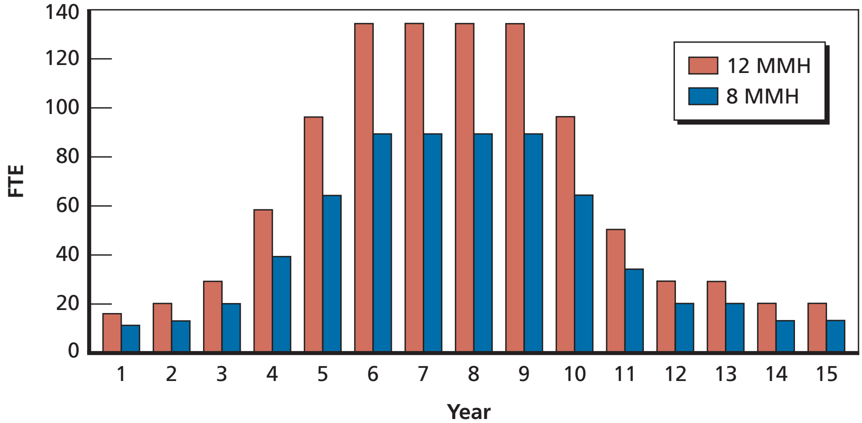
GENERAL DISTRIBUTION

Figure B.3
RAND Estimate of Number of FTE Piping/HVAC Draftsmen Required by Industry to Design a Large, Conventional Submarine, by Year



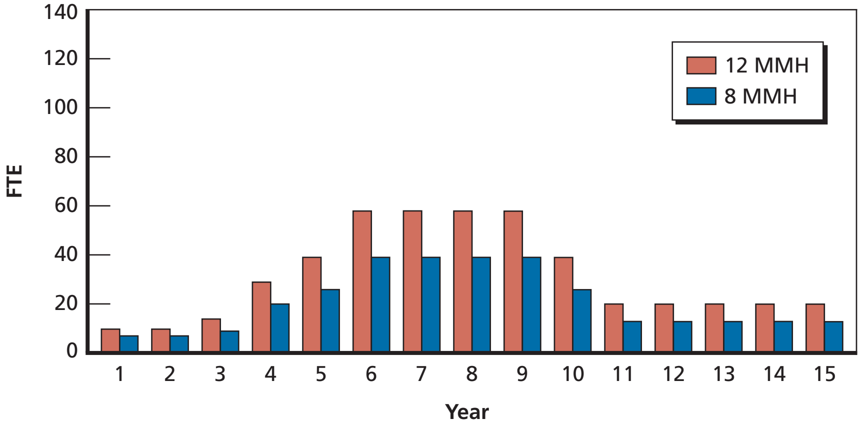
RAND *MG1033-B.3*

Figure B.4
RAND Estimate of Number of FTE Structural Draftsmen Required by Industry to Design a Large, Conventional Submarine, by Year



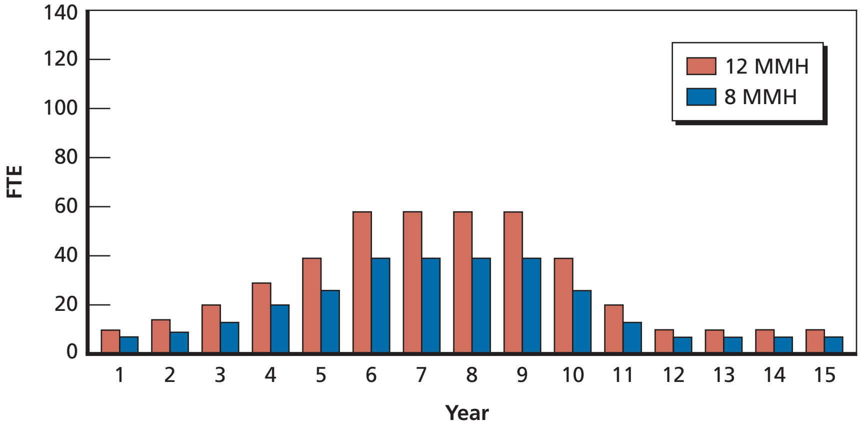
RAND *MG1033-B.4*

Figure B.5
RAND Estimate of Number of FTE Other Draftsmen Required by Industry to Design a Large, Conventional Submarine, by Year



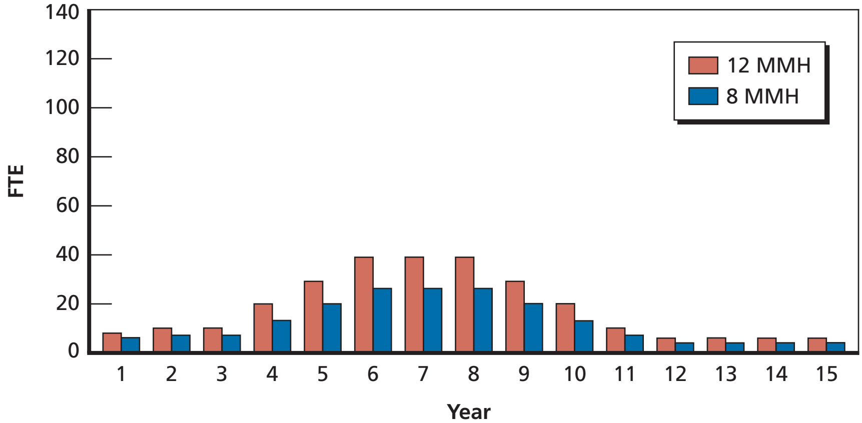
RAND *MG1033-B.5*

Figure B.6
RAND Estimate of Number of FTE Electrical Engineers Required by Industry to Design a Large, Conventional Submarine, by Year



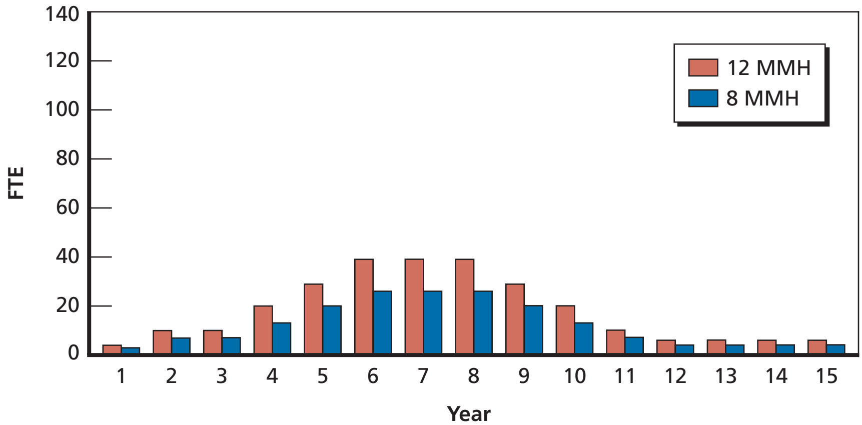
RAND *MG1033-B.6*

Figure B.7
RAND Estimate of Number of FTE Mechanical Engineers Required by Industry to Design a Large, Conventional Submarine, by Year



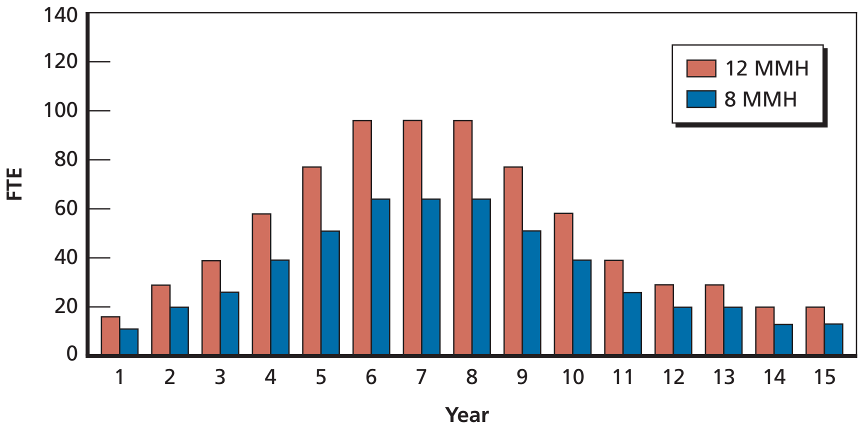
RAND *MG1033-B.7*

Figure B.8
RAND Estimate of Number of FTE Fluids Engineers Required by Industry to Design a Large, Conventional Submarine, by Year



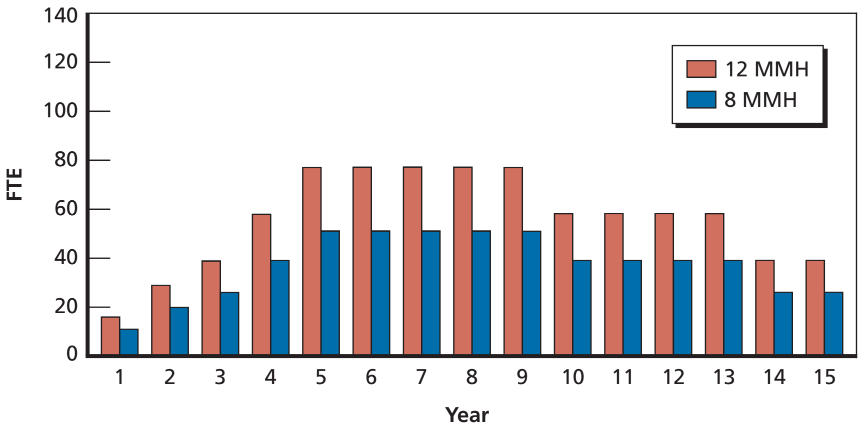
RAND *MG1033-B.8*

Figure B.9
RAND Estimate of Number of FTE Naval Architects/Structural Engineers Required by Industry to Design a Large, Conventional Submarine, by Year



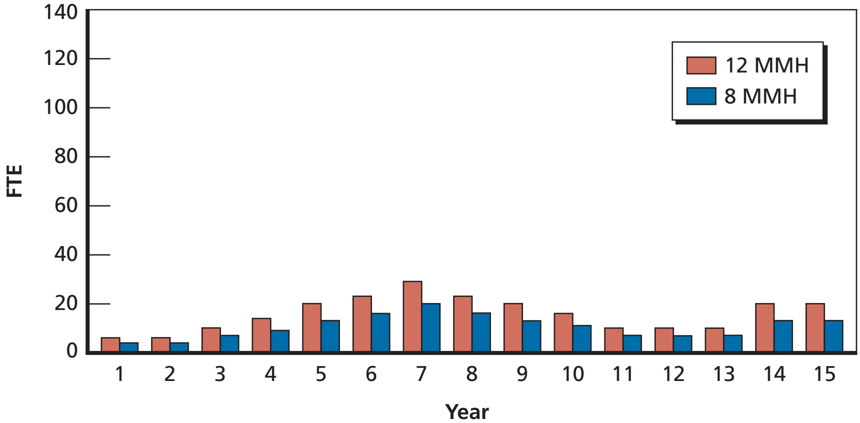
RAND *MG1033-B.9*

Figure B.10
RAND Estimate of Number of FTE Combat Systems Engineers Required by Industry to Design a Large, Conventional Submarine, by Year



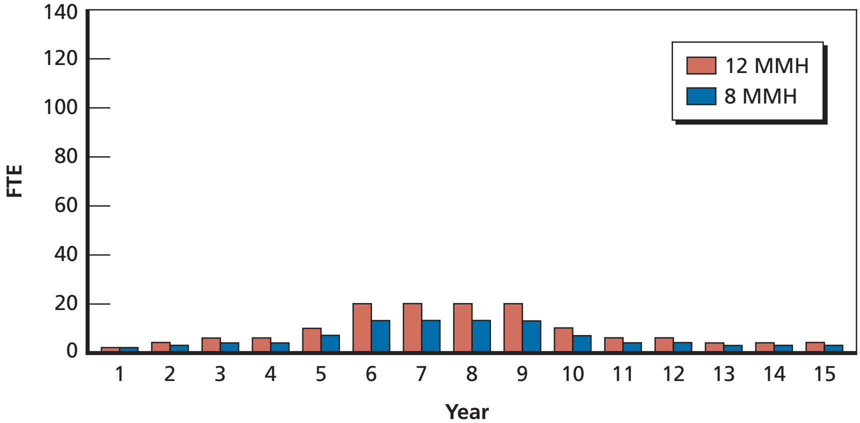
RAND *MG1033-B.10*

Figure B.11
RAND Estimate of Number of FTE Signature Analysts Required by Industry to Design a Large, Conventional Submarine, by Year



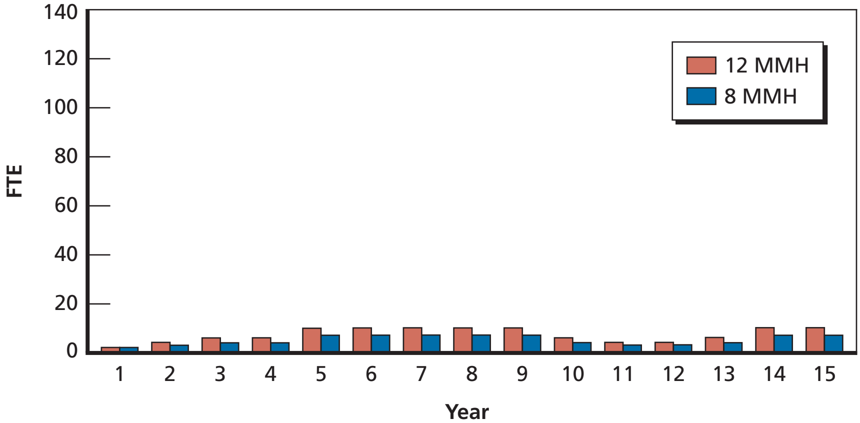
RAND *MG1033-B.11*

Figure B.12
RAND Estimate of Number of FTE Planning and Production Engineers Required by Industry to Design a Large, Conventional Submarine, by Year



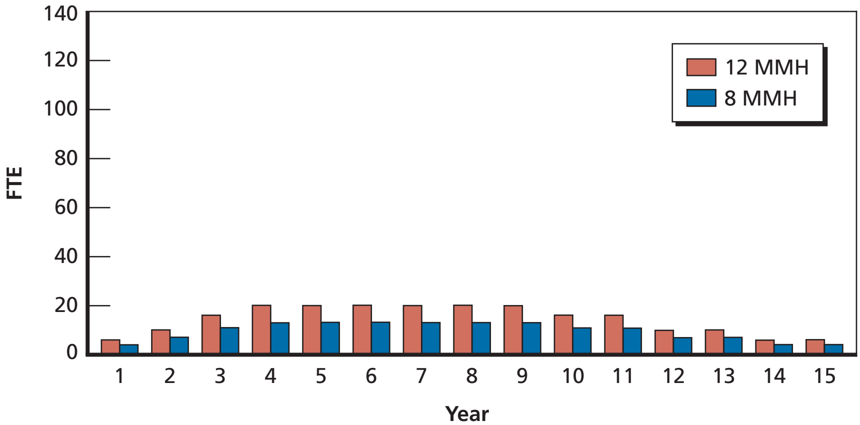
RAND *MG1033-B.12*

Figure B.13
RAND Estimate of Number of FTE Test Engineers Required by Industry to Design a Large, Conventional Submarine, by Year



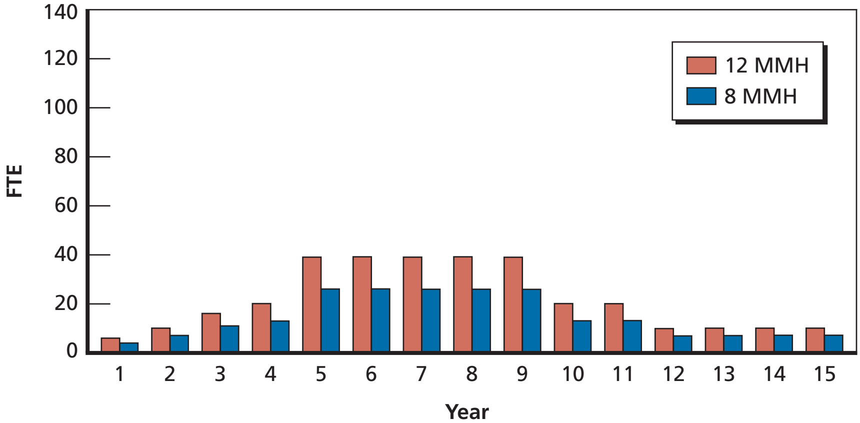
RAND *MG1033-B.13*

Figure B.14
RAND Estimate of Number of FTE Management Personnel Required by Industry to Design a Large, Conventional Submarine, by Year



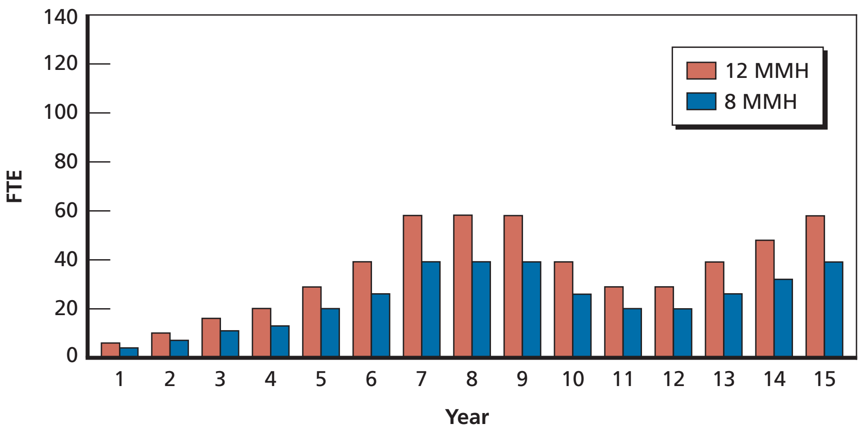
RAND *MG1033-B.14*

Figure B.15
RAND Estimate of Number of FTE Engineering Support Personnel Required by Industry to Design a Large, Conventional Submarine, by Year



RAND *MG1033-B.15*

Figure B.16
RAND Estimate of Number of FTE Other Engineering Personnel Required by Industry to Design a Large, Conventional Submarine, by Year



RAND *MG1033-B.16*

APPENDIX C

Implementing the Integrated Product and Process Development Approach

Although the IPPD approach can be more efficient and faster than the sequential design approach, it presents management challenges. Successful implementation of IPPD depends on establishing highly collaborative teaming and partnership arrangements. To do this, the customer and platform contractor must have (1) good collaborative design tools, (2) integrated project teams, (3) a well-constructed team organisation, and (4) a lack of barriers to communication and organisational stovepipes. We discuss the first three issues in this appendix.

Collaborative Design Tools

The complexity and simultaneity of the IPPD process place a great demand on information technology systems to support design. Chief amongst these tools is the 3D product model, which combines design, component, manufacturing, standards and specifications, cost data, and technical information into one system. Such a product model must do the following:

- support simultaneous collaboration of multiple users and have some method for configuration control of changes
- provide visualisation and "walk-through" capabilities to support manufacturability and supportability
- have links to manufacturing and support databases and equipment.

Development of such a system can be a significant undertaking. Even if off-the-shelf solutions exist, it is likely that some customisation of the tool will be necessary. Greater numbers of users and more-complicated designs require more-sophisticated systems. Furthermore, if users are not co-located at a single site, issues such as data transfer and security must be considered.

Integrated Project Teams

As a basic tenet of the process, IPPD forms a hierarchy of teams populated by cross-functional and multi-disciplined members. Integrated project teams (IPTs) are central to successfully implementing the IPPD process. Team composition comes from a variety of areas: operational, technical, manufacturing, business, and support. Team members move from functional perspective (i.e., representing their organisation) to a product perspective (i.e., their role is to produce a specific design product).

For submarine design, people knowledgeable of the construction and support processes are fully integrated into the design teams. This requires the teams to have as core members not only people in traditional design functions (such as naval architecture, HM&E system engineering, structures, acoustics, hydrodynamics, and others) but also experienced trade and support workers (such as shipfitters, welders, riggers, electricians, and pipefitters). Additionally, and perhaps most important, core team members also include government representatives, operational experts from the Navy, and significant sub-vendors who may provide major components to the design. Organisations with strong stovepipes or organisational affiliation will find it difficult to implement IPTs successfully.

Other considerations in forming IPTs as spelled out by the U.S. Under Secretary of Defense (Acquisition & Technology) are as follows:

> Critical to the formation of a successful IPT are: (1) all functional disciplines influencing the product throughout its lifetime should be represented on the team; (2) a clear understanding of the team's goals, responsibilities, and authority should be established among the business unit manager, programme and functional managers, as well as the IPT; and (3) identification of resource requirements such as staffing, funding, and facilities. The above can be defined in a team charter which provides guidance.[1]

It should be understood prior to committing to IPPD that team-based design has several unique dynamics associated with it. Chief amongst these is design decisions by consensus, a goal of IPPD, which ensures that all stakeholders have an opportunity to voice concerns but does not guarantee that all members will have all concerns satisfied. Decisions by consensus often take longer because broader issues are vetted by a larger number of participants. An incorrectly perceived belief is that team-based designs stagnate trying to reach a consensus in which all members are satisfied. The IPPD team remains accountable for executing its responsibilities in accordance with the integrated

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[1] "DoD Guide to Integrated Product and Process Development (Version 1.0)", Office of the Under Secretary of Defense (Acquisition & Technology), Washington, D.C., February 5, 1996.

master schedule, and the leader must have the authority, fortitude, and capacity to finalise the best available solution when the need arises.

Team Organisation

For complex systems like a submarine, a more complex organisational structure is required. Rather than a single IPT, multiple IPTs design the ship. The basic organisation tasked with executing the technical work of ship design and acquisition is a hierarchy of cross-functional teams, design/build/support teams, established at the platform contractor facilities. An experienced shipbuilding design/build/support organisation notionally consists of four types of design teams (process integration, system integration, major area, and major area integration) and two management/oversight teams (programme management and programme steering).

Design Teams

- *Process integration teams* (PITs) provide subject-matter experts in areas that cross multiple ship systems and are available to each of the product teams. Environmental compliance, safety, acoustics, logistics, testing, cost analysis, and risk management are typical PIT functions. PITs are often small, having only enough members to provide support to the system and area teams as required.
- *System integration teams* (SITs) are responsible for specific ship system designs. The SIT is responsible for designing the respective system to meet the ship specifications and operational requirements. Typical HM&E systems, such as hull structure, electrical power generation and distribution, high pressure air and gas systems, weapons handling and launch, piping, refrigeration, atmosphere revitalisation, hydraulics, and trim are typical SIT func-

tions. The extent and number of SITs is highly dependent on the specifics of the platform being designed, but 50 to 60 may be expected.[2]

- *Major area teams* (MATs) are established based on the manufacturing and assembly plan (MAP), and each is responsible for a single major construction module. While each SIT concentrates on the most efficient and effective system design and while most systems extend across multiple MAT interfaces throughout the ship, vessels are actually constructed by area or module. It is inefficient to sub-optimise each of 60 systems and then, within the arrangement constraints typical of a submarine design, to build a complete ship and enclose it in a pressure hull. The insight IPPD provides is that, while ships are often designed by system, they are more efficiently built and tested by area and the effort expended in designing for producibility as a large module is key to cost-effective designs. In light of this fact, MATs have managerial design control over the arrangements within their respective area. This allows the MAT to direct a specific SIT to make changes not necessarily best for the system design but in the best interests of the area build processes. An individual MAT is made up of representatives from each SIT, as well as construction trades, draftsmen, and process experts.

[2] It may be efficient to combine multiple systems within a common technical area into one SIT. For example, individual systems developed for trim, drain, potable water, sea water, fresh-water cooling, and sanitary may be combined into one "water systems" SIT. SIT membership varies considerably depending on the specific system, but ten personnel, not all permanent full-time, is reasonable. A core membership of team leader, Government representative, digital designers, and technical subject-matter experts is typical. SITs should include major vendors and customer technical representative and will use PIT subject-matter experts as required.

- The *major area integration team* (MAIT) is responsible for all areas and systems in the ship. With a view of the ship as a whole, the MAIT is the final arbitrator of differences between adjacent MATs. Its members come from each MAT as well as customer representatives and PIT experts, as required.

Management/Oversight Teams

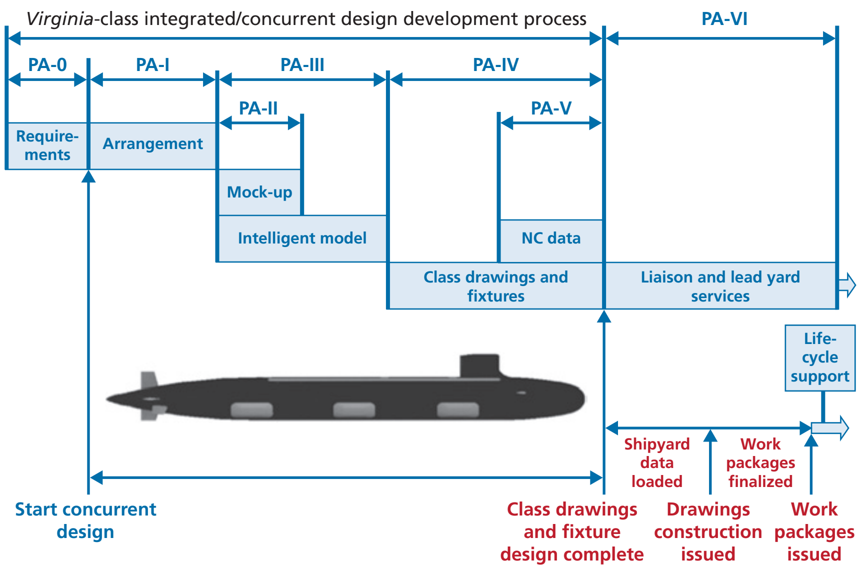
- The *programme management team* (PMT) is made up 110 of the major functional managers and has responsibility to execute the programme of record. Membership should include managers responsible for acquisition, cost assessment, integrated logistics, R&D, ship design, test and evaluation, financial analysis, and contracts. The PMT's core responsibility is to shield the design/build teams from as much non–value-added effort as possible. It does so by resolving issues effecting team efficiency, manning, space allocation, needed resources, briefings, etc., thereby allowing the design/build teams to concentrate on completing design tasks.
- *The programme steering group* (PSG) is a small group of senior programme leaders who are responsible for addressing issues and taskings that emerge from external sources. The PSG is the outward-facing programme management team that addresses issues generated external to the teams tasked with designing the ship. The PSG may consist of the programme manager and his deputy, business and financial manager, technical director, and a small number of others. The PSG will address issues external to the programme and those that extend beyond the current programme of record, budgeting, cost and schedule changes, configuration control changes, legislative affairs, public affairs, and media inquiries.

Virginia-Class Application of IPPD

As the *Virginia*-class submarine programme implemented the IPPD process, design phases were replaced by six product areas, which correspond to the various design products produced as the design matured (see Figure C.1). The product areas can be thought of as design phases; only the sequence of events was more streamlined as there was some overlap between product areas. The first product area was the Requirements Product Area (PA-0) where the specific characteristics of the future platform were established. Once the requirements were established, the specifications were turned into 3D arrangement models during the Arrangement Product Area (PA-I). Systems and sub-systems of the submarine were modelled within the ship structure to evaluate arrangements. Engineering analysis was performed and multiple design build teams met to identify possible design conflicts.

Once the arrangements were established, appropriate approval was required from the customer for the design to proceed. After approval was received from the customer, mock-up drawings were created for limited areas of the ship, and design products were further defined. The mock-up drawings were part of the Mock-Up Product Area (PA-II), and the product definition tasks were part of the Product Definition Product Area (PA-III). After the mock-up drawings were approved, system integration reviews, interactive engineering analysis, and approval of the intelligent model were required for final approval of the design configuration. These tasks were performed under the auspices of PA-III, which added "intelligence" to the model by defining material, parts, etc. Once mock-ups and product definition were approved, class drawings were produced and manufacturing support data were provided to construction activities.

Figure C.1
***Virginia*-Class Design Process**

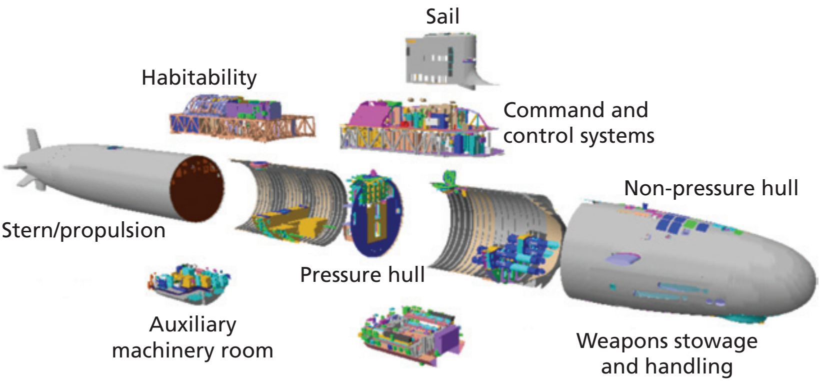


SOURCE: General Dynamics Electric Boat. Used with permission.
RAND *MG1033-C.1*

The development of class drawings was Product Area IV (PA-IV). The development of work package design data was performed as part of Product Area V (PA-V), or the Manufacturing Support Data PA. The final Product Area VI (PA-VI) was where work packages were finalised and drawings for construction were issued.

This process was carried out for each production module (see Figure C.2). The modules represented different parts of the submarine and were developed based on how the submarine would be produced. The deliverables associated with each product area were required for each module. However, the sequence in which tasks within each of

Figure C.2
***Virginia*-Class Design Modules**



SOURCE: General Dynamics Electric Boat. Used with permission.
RAND *MG1033-C.2*

the product areas were accomplished for each module was different—deliverables were driven by construction activities.

For the *Virginia*-class design programme, 15 MATs, each covering a contiguous area of the submarine, were formed to ensure that the design was producible and to facilitate construction planning. These teams were concerned with their areas and interfaced to other areas on a cradle-to-grave basis. Each team was co-led by a representative from Design and Engineering and one from Construction. The teams consisted of EB draftsmen and engineers representing various skills and engineering disciplines, as well as representatives from construction and planning and from the Navy technical community. Teams numbered from a few people to as many as 50, with certain individuals often serving on more than one team.

In addition to the MATs, 30 SITs were responsible for the systems that were distributed throughout the various modules. These teams both supplied manpower to the MATs and ensured cross-MAT communication. Providing overall direction and guidance to the various teams were two MAITs—one for the forward compartment and one for the aft compartment/engine room.

APPENDIX D

Submarine Design Tools[1]

This appendix expands upon and provides further details about design tools, test facilities, and other capabilities needed to create the modern submarine that we discussed in Chapter Five.[2]

According to the *Defence White Paper 2009*, Australia's Future Submarine will be more capable than *Collins*-class submarines. As a result, it is likely to extend the boundaries of capability for diesel-electric submarine technology. Its design will require optimisation, test

1 Material in this appendix is based on inputs from John Leadmon, former Director of Submarine Design and System Engineering for the Naval Sea Systems Command, and Ray Williams, former Director of Naval Architecture at Electric Boat. Related material is from the briefing "Integrating MIL-STD-882 System Safety Products into the Concurrent Engineering Approach to System Design, Build, Test, and Delivery Of Submarine Systems at Electric Boat", by Ricky Milnarik of the System Safety Engineering Group, Electric Boat. Further material was drawn from Roy Burcher and Louis Rydill, *Concepts in Submarine Design,* Cambridge University Press, 1995. Detailed material has been drawn from other cited sources.

2 As noted Chapter Two, ship design is perceived to transition through distinct phases of increasing fidelity and complexity. In the initial phase, concept design, design points are initiated to evaluate their gross characteristics. Sophisticated tools are not needed in the concept design phase. The final, contract design and detailed design, phases use the most sophisticated design tools. Accordingly, we focus here on simpler tools needed for concept design and the more sophisticated tools needed to complete contract design and detailed design efforts.

confirmation, technical rigor, and design and construction practices at least as sophisticated as, and in many respects greater than, those used to design the *Collins*-class vessels.

This appendix argues that while detailed design of a modern submarine could be conducted without state-of-the-art tools, proceeding without at least some of these tools risks sub-optimal designs. Such designs could harbor safety issues, be unable to perform intended missions or to deal with better-designed foreign submarines, or become obsolete prematurely.

Hundreds of capabilities are required to design a modern submarine. This appendix identifies and discusses those we have judged to be critical to the design of a modern submarine. We first describe each capability, after which we discuss the functionality of tools used to support it. Because of the limited time and resources available for this study, we were not able to evaluate the suitability of those potential tools in designing a future Australian submarine. We mention specific software tools to illustrate the types of software needed; such discussions should not be interpreted as endorsements. Similarly, we mention specific facilities, but these should not be interpreted as endorsements.

It should be noted that design capabilities can overlap. For example, shock qualification (which considers the response of the submarine to explosions) and structural analysis (which considers internal and external structures and components for operational and shock loading) clearly overlap.

Naval Architecture

The iterative process of ship design begins with concept design. The development of concept design "point studies" is an iterative process that uses relatively simple tools. Point study development includes ship arrangements, displacement, weights, hull form, speed, payloads, signatures, and cost with the goal of achieving attributes needed for future operations and missions.

The building block approach to point studies, one of several possible approaches, uses known component blocks with given space and weight. A diesel generator plant and its associated equipment might be one such component block. With the assembly of component blocks, additional features, such as necessary ballast tank requirements, can be estimated. The end result is a rough design that can be evaluated in both engineering and operational terms. For example, a rough calculation is needed to evaluate hydrostatics, centre of gravity, and weights. The adequacy of growth margins can also be evaluated here and the performance of the point study can be estimated. Failure to meet engineering or performance requirements results in another iteration.

The building block approach was initially employed without computing aids and, in principle, could be conducted in the future without such aids. However, the computational techniques involved are relatively simple and lend themselves to computer simulation. In any case, the quality of data for the building blocks is important, and the variety of building blocks for which data are available can limit design innovation. Alternatively, more forward-looking designs can be explored using "what if" component blocks.[3]

A basic point here is that lack of relatively simple automated tools can limit the quality of point designs and restrict the exploration of innovative submarine designs—resulting in designs that are sub-optimised.

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[3] We note that other comparably simple approaches to developing point designs exist. See Burcher and Rydill, 1995, pp. 247–275.

Submarine Arrangements

Arrangement work—the placement and integration of all pipes, valves, pumps, motors, electrical wiring, switchboards, batteries, structures, and foundations in a vessel and the provision for access to each of these components—is a challenging area of submarine design.

Arrangement work forms the foundation upon which most other mechanical analysis work is based. It must be performed in a manner that allows efficient construction of the submarine, comfortable living onboard, effective operations at sea, and cost-effective maintenance over the life of the submarine. Arrangement is even more challenging if there is a desire for an unspecified future capability. The flexibility and adaptability characteristics of a good submarine arrangement can be daunting. Errors in this area are usually discovered later in the programme when corrections are most expensive.

No universities or schools teach this technical discipline. Most experts in this area have learned their craft from their predecessors. Arrangement work can and was performed by draftsmen for hundreds of years in the maritime industry. More recently, computerised arrangement tools have replaced the traditional drafting skills.

Commercially available software suites have been used successfully for arrangements. However, none of them is submarine-specific. Moreover, they require time and effort before personnel can effectively produce detailed two-dimensional (2D) and 3D submarine drawings.

Applied Mechanics

Design and test capabilities related to applied mechanics fall into the following two groups:

- capabilities to design and analyse submarine structures and components for all static, dynamic, and vibration-induced loading conditions
- capabilities to predict transient response of marine vehicles to underwater explosions.

Both areas of analysis are appropriate to the contract design and detailed design phases of the design process. They apply physical laws, mathematics, and failure theories to internal and external submarine structures to determine deformations, internal forces, and stresses.[4]

Strength, stiffness, and (dynamic/static) stiffness ratios are traditional study areas in mechanical engineering. In simple cases, engineering handbook–level tools may be adequate to address these problems. Vibration analysis, being more complex, requires sophisticated tools and test facilities. These tools aid in the determination of transfer functions and the effects of design changes intended to improve performance. Transient response analysis is also complex. In the case of transient response to underwater explosions, underwater explosion phenomena need to be understood, along with structural dynamics,

[4] A note for non-technical readers: A large diesel engine mounted on a foundation illustrates several different types of loads. *Static loads* are represented by the gravitational force of the engine on the foundation—the engine is essentially fixed in magnitude and location. These loads relate to the strength of the foundation. *Dynamic loads* are represented by the twisting force, or torque, presented by the engine as it changes speed or load. These loads relate to the stiffness, or rigidity, of the foundation. *Vibration-induced loads* are represented by the vibration resulting from the firing of the engine's cylinders. The loads relate to a complex of issues: Does the foundation's mass damp the vibration? Does the foundation conduct vibration to other structures? What is the (mathematical) transfer function of the foundation to other structures? Does the vibration of the engine excite vibration in the foundation—possibly worsening noise or even leading to structural damage? *Transient responses* are represented by possible shifting or movement of the engine on its foundation due to normal or emergency ship motion or damage to the engine following an explosion or other significant event.

fluid-structure interactions, fluid volume modelling (including cavitation), shock characteristics, and so on. Considerable research has been conducted on transient responses to explosions: Courses on the topic, related software, and professional services are available. The analysis of transient responses to explosions is treated later in this appendix, under structural analysis.

Applied mechanics tools are used to minimise the weight that a draftsman might allocate to structures and foundations and therefore allow, for example, additional fuel or more weapons. However, much less sophisticated, empirical, and rule of thumb–based tools can be used. They result in a good level of capability, albeit at a weight penalty in structures and foundations.[5]

[5] The dynamic design analysis method (DDAM) is a software tool used successfully in the United States for many years. DDAM is an all-encompassing tool that accounts for dynamic and transient inputs. It is a regimented collection of response spectrum procedures that is used by the U.S. Navy to estimate the peak linear response of shipboard equipment when a ship is subjected to an underwater explosion. ABAQUS, developed by Dassault Systèmes, is another such tool. DDAM tailored for ABAQUS is provided free of charge to ABAQUS users; downloading instructions are available. See "ABAQUS Adds DDAM Capability for Marine Design", *Industrial Equipment News,* no date. The NASA Structural Analysis (NASTRAN) programme was originally developed by the National Aeronautics and Space Administration in the United States and continues to be further refined by a number of companies, including MSC Software, NEi Software (NEi NASTRAN), and Siemens PLM Software (NX NASTRAN). DDAM, in conjunction with NASTRAN and Finite Element Analysis methods, provides excellent results. All are commercially available and are not difficult to learn. Additionally, DDAM with ABAQUS has been utilized to analyze various structural problems on submarines. Currently, ABAQUS has been fully transitioned to SIMULIA, a Dassault Systèmes product. CATIA is one example of a sophisticated, commercially available software system for applied mechanics and related analysis. CATIA was used in the design of the USS *Virginia*, the DDG-1000 destroyer, and has been used by the Boeing Corporation for aircraft design. Other software packages more or less equivalent to CATIA are available. These include Bentley's STAAD.Pro and variants of NASTRAN. Supporting software is also available.

Shock Qualification

Shock qualification is closely related to the analysis of transient responses and is appropriate to the contract design and detailed design phases. Shock qualification by analysis requires the capability to perform fluid-structure interaction calculations, including finite-element models of floating and submerged vehicles. Shock qualification also includes shock qualification by test and by extension of results. Considerable research has been conducted in this area, and various resources are available. Australian authorities already perform extensive shock testing at the component and system levels, so further discussion of tools in this area is not necessary.

Structural Analysis

Structural analysis includes the capability to perform dynamic analysis of internal and external structures and components for operational and shock loading in accordance with specification requirements. It also includes the capability to perform fracture and fatigue analysis of internal and external structures for operationally induced cyclic loads. Finally, it includes the capability to perform fluid-structure interaction shock analysis to evaluate internal and external structures and components for various underwater explosions. Such analyses are appropriate to the contract design and detailed design phases of the design process.

These various analyses require different tools. Failure analysis for a submarine hull as a whole, for example, is a very different problem from failure analysis for internal structures. The former requires sophisticated structural analysis software and significant computational resources, whereas the latter can be conducted using relatively simple models and modest computational power, if appropriate materiel data are available. One exception here is for corrosion effects on material fatigue, which is a complex topic. Another exception is for unacceptable deformation. Practically speaking, 3D design tools are needed to detect and evaluate impingement through deformation.

Fluid Dynamics

Fluid-dynamics analysis in submarine design treats both internal flows (e.g., piping) and external flows (e.g., appendages). Both types of flows can be analysed and modelled in two- and three-dimensional representations using computational fluid dynamics (CFD) methods. Such representations provide hydrodynamic load estimates for structural engineers and naval architects. CFD models produce the best results in fluid dynamics. They aid the draftsman in producing minimum-weight structures, systems, and components.

A CFD grid for a control surface is shown in Figure D.1,[6] which shows the extension of the grid beyond the hull and control surface.

Fluid-dynamics analysis is appropriate to the contract design and detailed design phases.

Less weight-conscious methods have been used successfully. These tools are semi-empirically based and follow well-established mechanical engineering principles.[7] An engineering graduate from a certified

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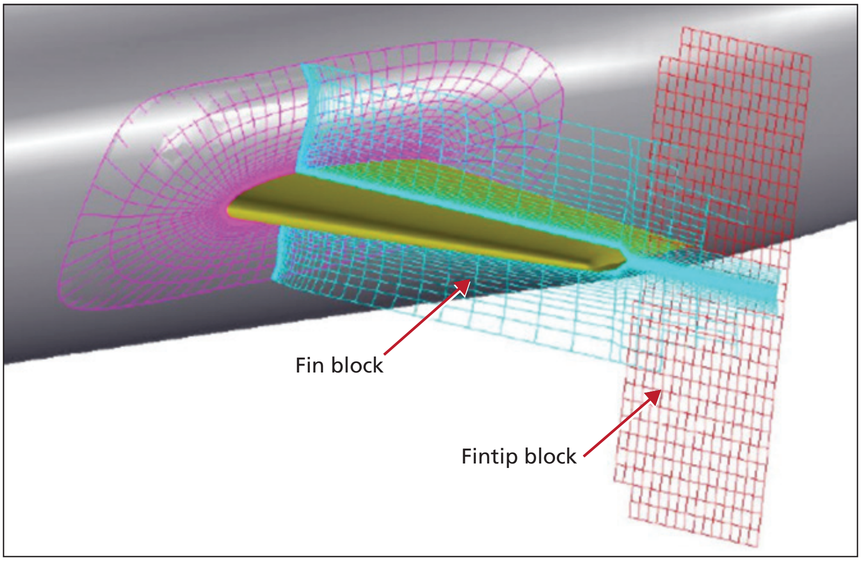
6 James C. Huan and Manivannan Kandasamy, "High Fidelity Viscous Flow Simulations for High-Speed Sealift (HSSL) Performance Confirmation", *9th Symposium on Overset Composite Grid and Solution Technology,* The Pennsylvania State University, October 14–16, 2008.

7 See, for example, D. A. Jones, D. B. Clarke, I. B. Brayshaw, J. L. Barillon, and B. Anderson, *The Calculation of Hydrodynamic Coefficients for Underwater Vehicles*, Canberra: Defence Science and Technology Organisation, DSTO-TR-1329, 2002.

Figure D.1
CFD Grid for a Control Fin



SOURCE: 9th Symposium on Overset Composite Grid and Solution Technology, The Pennsylvania State University, October 14–16, 2008, "*High Fidelity Viscous Flow Simulations for High-Speed Sealift (HSSL) Performance Confirmation*" by James C. Huan and Manivannan Kandasamy. Used with permission.
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engineering college or university should be able to perform these and other required computations.

Analysing Internal Fluid Flows: Fluid-System Analysis

Fluid delivery systems in submarines include plumbing, hydraulics, drains, compressed air systems, and seawater and freshwater cooling systems. Fluid-system designs must be developed to meet demands and to meet requirements in such areas as noise and heat balance. Fluid-system analysis entails the ability to develop fluid-system diagrams, calculate pressure drops, size pipes and components, select materials, design arrangement, and engineer acoustic isolation. Such analyses are appropriate only to the contract design and detailed design phases of the design process.

For the most part, the design of such systems is relatively straightforward. Any mechanical engineering undergraduate with a rudimentary background in fluid mechanics should be capable of developing diagrams and sizing pipes for correct flow rates. However, the number of configurations arising from multiple loops and pumps, sizing options, and alternative materials can create an unwieldy number of cases. Automated systems increase the number of configurations that can be explored and could lead to better solutions.

The proper selection of piping-system components, such as valves, suitable for submarine service is more difficult. The acoustic analysis of a fluid system can be more challenging than other aspects of fluid system design. A "test loop", fitted with sensitive acoustic measurement equipment, is often used to design and confirm the design of piping systems.

Heat flow in pipes (related to pipe stress) is another possible issue that may require more-advanced tools or experimentation.

Analysing Internal Fluid Flows: Pipe-Stress Analysis

Pipe-stress analysis addresses the static and dynamic loading resulting from the effects of gravity, submarine movement, temperature changes, internal and external pressure changes, and changes in fluid flow rates. It employs piping-failure theory and metallurgical data to examine issues such as pipe thickness, back-wall thinning in pipe bends, erosion, material, and stresses and loads (e.g., continuous, cyclic, or occasional) placed on pipes and pipe joints; to evaluate stresses in welding, forming, and construction processes; and to assess relationships between pipe fatigue and piping-system layout and mounting.

It is another aspect of the design process that is appropriate to the contract design and detailed design phases.

A number of commercially available software suites perform this type of analysis, and many are offered with training courses. Recent engineering graduates should be able to master this type of analysis once they are provided with some training.

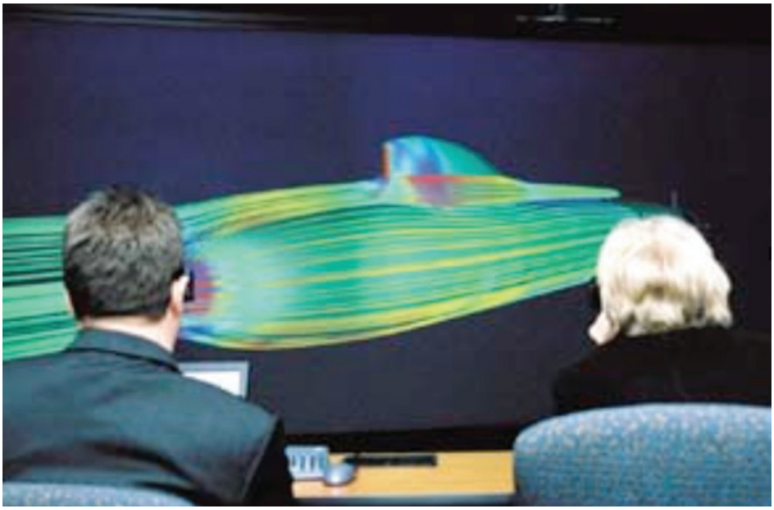
Analysing External Fluid Flows: Hydrodynamics

Hydrodynamics in submarine design treats flow of water over the entire exterior of the submarine (both hull and appendages). Whereas fluid dynamics treats the response of the submarine to flow, hydrodynamics treats the ocean's response to submarine movement.

The science of hydrodynamics has recently evolved from a semi-empirical field to one using sophisticated CFD techniques. Perhaps the simplest hydrodynamic problem confronting ship designers is the relationship between ship speed and power. Semi-empirical tools with drag estimates can be useful here in concept design efforts. More-complex problems (such as optimising the shape and size of submarine control surfaces, calculating loads and torque on control surfaces during manoeuvres, and assessing ships' ability to safely reach the surface from depth under casualty conditions or depth excursions) demand more complex and sophisticated tools. The output of such tools is illustrated in Figure D.2.

Submarines can be designed without using full-blown CFD computations. Consider the *Los Angeles* class, which was the last submarine class designed for the U.S. Navy without CFD tools. Scale-model tests employing tow tanks, model basins, and water tunnels were used heav-

Figure D.2
Hydrodynamic Flow Visualisation



SOURCE: U.S. Naval Sea Systems Command, Naval Surface Warfare Center, Carderock Division.
RAND *MG1033-D.2*

ily in the design of the *Los Angeles* (SSN-688) and still provide valuable hydrodynamic data in submarine design.[8]

Excellent results can be obtained if these tests are combined with laser Doppler velocimetry measurement techniques. Large cavitation channel (sometimes called circulation) water tunnels—such as the Garfield Thomas Water Tunnel at the Applied Research Laboratory, The Pennsylvania State University—can provide additional data for design-

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8 Relatively small (about 1/20 scale) models of submarine designs are either towed or run free—for example, in the David Taylor Model Basin—with variations in displacement, trim, and appendages to provide accurate resistance measurements, manoeuvring coefficients, and moments plus dynamic response behavior during manoeuvres.

ers. These and other facilities equipped with laser Doppler velocimetry equipment can provide excellent data without CFD calculations.

Another hydrodynamics tool is a large-scale vehicle (LSV). Roughly a quarter-scale model of a submarine design, an LSV operates as an autonomous vehicle. LSVs are empirical tools for evaluating submarine hydrodynamics, especially when designers are seeking data that cannot be discerned in the small-scale models because of the minute magnitudes involved. LSVs provide a unique capability to measure radiated noise under submerged conditions.[9]

The choice of empirical data, computationally based data, or empirical data supplemented by computational data depends on (1) available facilities, either government-owned or contracted from companies or universities, (2) the amount of engineering education of the draftsmen, and (3) the level of risk to be accepted, mitigated, or avoided. High-end CFD tools drive risk to a minimum. Semi-empirical tools carry higher (but still low) risks.

Mechanical System and Component Design

Mechanical systems and components on submarines include weapons handling and launch systems, retractable masts, steering and diving systems, ship hatches and doors, and winches.

No unique tools are needed to design mechanical systems and components. It does require the capability to develop mechanical designs that meet design and operational requirements. It also requires

[9] Although Australia is interested in developing a domestic LSV capability, LSVs currently are a capability unique to the United States. The United States has used LSVs to advance the state of the art of CFD and other advanced acoustical analysis methods. As discussed later, LSVs also provide a unique capability to measure own-ship noise.

in-depth knowledge of engineering principles, specifications, hydraulics, and a solid understanding of acoustics, shock, vibration, material science, and manufacturing processes.

Propulsion System Analysis

The design of propulsion systems is complex and overlaps other areas of submarine design.[10] Tasks for propulsion system analysis (in contract design and detailed design) include

- hydrodynamic design and model testing; speed/powering and fuel endurance analysis
- equipment sizing, selection, procurement, and evaluation
- mechanical and electric drive-system design
- propulsion system trade-off studies to balance performance and cost
- shaft sizing, arrangement, and alignment studies
- reliability, maintainability, and availability analyses; failure mode, effects, and criticality analyses
- equipment and hull girder vibration analysis
- airborne and structure-borne noise predictions (for radiated and self-noise)
- shock qualification
- intake/uptake testing/analysis
- dynamic response analysis
- controls system engineering

[10] We ignore these overlaps here in order to provide a coherent description of propulsion system analysis.

- total ownership cost analysis
- land-based test facility design.

Much of this analysis can be conducted with computer models (including models used for other tasks, such as hydrodynamics analysis and structural analysis). However, as noted, land-based testing is also useful.[11] Land-based systems have been used to test and evaluate new equipment and software, including testing the reliability of propulsion systems, engine-controller systems, upgraded components and prototypes, and hybrid propulsion-power systems. These land-based systems also have been used to evaluate conditions-based maintenance algorithms and to conduct crew training.

Any Australian LBES should be designed and configured to test components—including diesel propulsion engines, batteries, diesel generators, fuel delivery, shaft, gearboxes, controller system, and other new technologies—in arrangements identical to those planned for the Future Submarine. It should also include any AIP systems. Intake and uptake systems designed to represent the performance of shipboard systems are also desirable. Sensors to measure vibration and noise are also desirable as tools to validate predictions and test design modifications. Ideally, this LBES would use a full-scale replica of the engine

[11] In the United States, the land-based experiment system (LBES) operated in Philadelphia, Pennsylvania, by the Carderock division of U.S. Navy's Naval Sea Command, is a facility for improving the design and reliability of propulsion systems in the U.S. Navy. Separate sites have been constructed for a variety of U.S. Navy ships, including the DDG-51 destroyer, the CG-47 cruiser, and the LPD-17 amphibious transport dock ship. The DDG-51 site, in particular, consists of a full-scale replica of part of the engineering plant of a DDG-51 class destroyer, including two GE LM-2500 marine gas turbines and associated auxiliary equipment (including shafting, bearings, fuel systems, lube oil, low-pressure air, and cooling water) configured as an engine room in the DDG-51 destroyer. A water brake tank is used to provide realistic loads to the propulsion system. See Eric McFetridge, "Gas Turbine Test Facility Being Constructed to Meet Navy Needs", *Wavelengths Online,* February 25, 2004.

compartment of the Future Submarine for vibration and noise measurement/reduction. An Australian LBES for the Future Submarine could be used with accelerated testing to identify propulsion system problems relatively early in the design process, to improve the reliability of the propulsion system and to minimise vibration and noise prior to the system's installation in the lead ship.[12]

Acoustic Analysis

Acoustic analysis addresses the total radiated noise signature of submarine designs. This includes radiated noise that an enemy might detect, self-noise that that would degrade performance of the design submarine's sonar sensors, the sources of the acoustic energy onboard the submarine, the mathematical transfer functions that allow this energy to get into the water, or other onboard structures and systems. The mathematical transfer functions that result in structure-borne, fluid-borne, or air-borne noise are challenging to determine because acoustic-flanking paths can be difficult to identify.

Submarine acoustic analysis also includes how the submarine and its structures, systems, and components respond to approaching acoustic wave fronts. Determining the extent to which wave fronts are reflected, diffused, or absorbed is challenging and requires in-depth knowledge, sophisticated analysis tools, plus semi-empirical models and test facilities. Similar, but distinct, tools are required for the analysis of the radiated and self-noise signatures.

Submarines have many noise sources: hydroacoustically induced noise emanating from external structures that are excited by the flow

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[12] Such an LBES might have improved the reliability of the propulsion plant in the *Collins* class. It would not have prevented problems experienced with the 15-tank diesel fuel system.

field around the submarine; noise from rotating machinery (motors, fans, pumps, valves, and actuators); noise from electrical components (transformers, inverters, converters and electrical switchage, harmonic feedback from electrical machinery); and noise from fluids (air, water, or hydraulics) flowing inside their pipes and ducts. Many of these noise sources can be identified and treated or designed to be less observable. Much more difficult to tackle are noise signatures created by structural components that become excited due to propeller shaft rotations or propeller blade rate interactions. Generally, these sources are low-frequency in nature, difficult to identify, and difficult to correct; they can have tremendous propagation ranges. Such noise analyses can only occur during the contract design and detailed design phases.

The primary goal in this area is ensuring that the submarine's systems meet radiated, platform, and airborne noise requirements. In U.S. submarine development, acoustic-system engineers evaluate submarine systems and components and develop optimal noise-control features and allowable acoustic amplitudes for the submarine components, in order to ensure that the ship's overall silencing goals are met. Laboratory and shipboard tests are performed to determine the acoustic performance of noise-critical systems, noise-control features, and shipboard structures.

Structural Acoustic Analysis

Structural acoustic analysis is defined as the capability to design and analyze ship systems for the purpose of understanding and mitigating radiated noise levels. This includes the design and analysis of structures; components; and noise-mitigation devices, arrangements, features, and treatments. For example, the presence of a fluid inside a tank structure can significantly change the vibration characteristics of the containing structure. To determine the extent of this effect, engineers must model all relevant dynamics; especially the fluid–structure coupling that represents the interaction between these two domains. Models must, therefore, account for factors (such as mass, stiffness, and damping) that the fluid adds to the overall system.

Structural acoustic analysis also includes the analysis and mitigation of noise resulting from propeller-induced forces in the submarine that radiate in the far field. In light of the level of detail required for such analyses, they are sensible only in the contract design and detailed design phases.

Tools for structural acoustic analysis include software packages to aid determining noise sources and the affects of vibration isolation systems, equipment to measure vibration and noise levels, and test facilities.

Hydroacoustic Analysis

Hydroacoustic analysis in the context of submarine design is the ability to predict and control flow-induced noise and vibration. It includes prediction of hydroacoustic forcing functions (i.e., vibration sources) and analysis of structural response to and radiation resulting from these forcing functions. Hydroacoustic analysis includes noise resulting from flow over the hull, especially noise generated by structural interaction of the propellers and structural interactions caused by the propeller.

Tools for hydroacoustic analysis include ABAQUS/SIMULIA (mentioned above), which provides a number of capabilities in the area of structural-acoustic analysis. In addition to pure acoustic analysis features, ABAQUS includes the capability to couple non-linear structural analyses with linear acoustic analyses using several different methods.[13]

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[13] Applied Physical Sciences (APS) performs structural acoustic analysis for the U.S. Navy. APS conducts applied research and development in structural acoustics for the Office of Naval Research, NAVSEA, General Dynamics Electric Boat, and other prime contractors. Its current focus is on computationally efficient numerical tools that can be used to evaluate next-generation propulsion systems and signature reduction systems. APS research includes

Software Development

Automation is used in modern submarines to reduce crew complement requirements and to increase speed of response in critical situations. To illustrate, in older (essentially manual) submarines, a helmsman controlled or changed course, a forward planesman controlled or changed depth, and an after planesman controlled or changed pitch. A single helmsman now replaces these three crewmembers by giving inputs to a computer that controls course, depth, and pitch. Valves that were opened and closed manually on older submarines are now opened and closed automatically or with the push of a button. A similar situation exists for system monitoring.

Reduction in crew complement has the advantage of reducing submarine size requirements. Ship automation can increase speed of response by replacing long chains of command (using verbal communication) with nearly instantaneous actions. Automation however brings risks such as when an automated system reacts inappropriately to unanticipated conditions. Automation also brings complexity through need for redundancy in automated systems.

Software development for submarines requires the capability to analyse, design, code, and test software for unique submarine systems, such as mechanical, propulsion, and electrical. This includes analysis of a range of factors—requirements, process definition, database design, code and programme management, simulation fidelity, sensor inputs,

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development of models to predict and measure wave propagation phenomena in structures. LSVs are used for hydroacoustic noise predictions. In addition to the LSV itself, a system for tracking and controlling the LSV, a system of hydrophone arrays to collect noise from the LSV as it passes, and an onboard data collection system to record self-noise signatures and operating parameters are needed for hydroacoustic noise predictions. The roughly one-quarter scale used for LSVs is the smallest supporting such analyses by the U.S. Navy. Use of a one-tenth-scale vehicle might not yield the level of quieting sought by the U.S. Navy.

and test procedures. Knowledge of the requirements for independent verification, validation, and accreditation of any written software is essential for software quality control. Without independent verification that software will perform as intended under all conditions, there will be a risk of unexpected surprises/consequences when the product is placed in service.

Simulation facilities and software development tools are needed for the development of software for submarines.

Electrical Analysis

The electrical system is one of the most extensive and pervasive systems in a diesel-electric submarine.[14] It is extensive in the sense that it extends from the propulsion motor in the stern, to batteries forward, and on to the torpedo room in the bow. It is pervasive in that electrical power is needed to operate or control systems associated with propulsion systems, control systems, hotel systems, and functions related to navigation, communications, weapons, sensors, and emergency response.[15]

The design of an electrical power system is analogous to the design of fluid delivery systems described above. Reliability of power supply is an additional consideration, along with operating flexibility and safety. The demands for direct and alternating current power must be identified; generators, batteries, and cables must be sized; and arrangements must be developed. This requires a thorough understanding of power distribution component function, operational, interface, and arrange-

[14] Main components of the electrical power system are main generators, batteries, main switchgear, main power distribution equipment, system protection equipment, and system control and monitoring.

[15] Burcher and Rydill, 1995, pp. 214–215.

ment requirements; quality and safety features; and material, fabrication, and cleanliness requirements. It also requires the capability to perform electromagnetic analysis of machinery (e.g., motors and generators) to determine performance attributes, signatures and viability, and the capability to develop electrical system diagrams, cable sizing, and component arrangements.

Design capability also requires experience and extensive knowledge of

- diesel generators—including functional, operational, and arrangement and installation requirements
- any AIP systems
- batteries—including capability to perform loading and battery endurance evaluations that define/validate submarine battery systems. This capability includes power and voltage analysis, which evaluates the submarine system's capability to distribute energy to the electric plant or consume energy for battery charging. It also includes technical skills in cooling, ventilation, arrangements, and shipboard installation methods
- propulsion motors—including experience and extensive knowledge of the propulsion system, including the design, installation, adjustment, operation, trouble-shooting, and repair of the drive motor, drive train, and control system.

Finally, an electrical system capable of functioning adequately under normal conditions can fail catastrophically otherwise. Thus, analyses of possible failure modes for the electrical system under extraordinary conditions (such as crash-backs) or equipment casualties is needed.

Radar Analysis (Radar Cross Section—Target Strength)

Radar analysis for diesel-electric submarines, especially diesel-electric submarines that have snorkels, primarily addresses masts (periscopes, antennas, and the snorkel). Specialised anti-submarine–warfare radars are designed to detect small objects against the radar clutter generated by the sea surface. While important in detecting targets, emitter power and distance do not affect the calculation of a radar cross section (RCS) because the RCS is (approximately) only a property of the target.

Hence, the heads of submarine masts should be designed with the smallest possible geometric size. Facets (like those on the U.S. F-117 aircraft) can be incorporated into snorkel heads to reduce the likelihood of multiple returns (and hence tracking). The surfaces of mastheads can also be covered with radar-absorbing material to further reduce RCS and increase the difficulty of tracking the submarine by radar.

RCS models and models treating radar-absorbing material are used for radar analysis. In the design phase, it is often desirable to employ a computer to estimate the RCS before fabricating an actual object. Many iterations of this prediction process can be performed quickly at low cost, whereas use of a measurement range is often time-consuming, expensive, and error-prone.

Numerous RCS calculation and simulation software packages are available commercially.[16]

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[16] Sources include AEMCs, Artemisia, CADRCS, EMAC, Epsilon, Lucernhammer MT, RadBase, and the Visual Basic Ram/Radome Optimisation Program (VBROP). Lucernhammer MT was developed to simulate electromagnetic signatures of military vehicles and hardware. It is restricted by the Arms Export Control Act of 1976, and is included in the U.S. Department of State's International Traffic in Arms Regulations (ITAR) list.

Systems Engineering

In the context of submarine design, systems engineering technically develops, integrates, and optimises all systems in the ship and prepares technical deliverables by (1) developing and evaluating system concepts and new components; conducting trade-off studies; and developing system diagrams, class drawings, component specifications, etc. and (2) performing safety analyses on new and significantly modified legacy ship systems and components. Typical submarine systems are displayed in Table D.1.

Systems engineering studies tend to address one-off problems and so require the development of specialised tools.

Design Project Management Tools

Design project management tools are used to formalise the tasking and scheduling relationships associated with designing, building, and testing the submarine. These tools define major ship modules and formalise the sequence in which components are procured; the integration of deck structures; and the building, installation, and testing of major sections of the ship. An integrated master schedule may be fully populated with upwards of 150,000 tasks supporting critical path method[17] and programme evaluation and review techniques. Such a robust

[17] The *critical path method* is a widely used management technique that has been successfully employed since the 1950s. It begins with a list of activities required to complete a project (typically organized into a work breakdown structure). The next step involves determining the time required to complete each activity and identify dependencies amongst the activities. After that, activity paths are identified along with the time required to complete each activity. The time to complete the project is dependent on the path requiring the most time.

Table D.1
Typical Submarine Systems

Submerger signal ejector system	Garbage ejector system	Tactical data handling system
Torpedo discharge system	Trim and drain system	Propulsion plant
Vertical launch system	Low- and high-pressure air system	Fresh water system
Weapons handling system	Steering and diving hydraulic system	Main seawater system
Communications (radio) system	HVAC system	Ship entertainment system
Combat control system Tactical data handling system	Ship service hydraulic system	AC power/interior system
Combat weapon launch control system	Ship control system	Masts and antennas
Navigation system	Echo-Sounder (Fathometer)	Atmosphere monitoring system
Sensor system	AC electrical power distribution system	Interior communication system
Total ship monitoring system	Direct current electrical power system	Auxiliary seawater
Non-tactical data processing system	Normal and emergency lighting system	Main ballast tank vent system
Escape and rescue system	Fire fighting system	Pressure low blow system
Propulsion engines	Air induction and exhaust system	Propulsion shafting, couplings, and bearings system
Diesel engine fuel oil system	Diesel engine management system	Main battery system (including battery monitoring) system
Cavity and gravity drain system	Variable ballast (compensation) system	Main shaft seal (both normal and emergency) system

scheduling system provides the Government and platform contractor with early insights into emerging problems and other areas of concern throughout the programme.

These tools also facilitate the management of growth and margin during the iterative process of submarine design because design changes in one area can ripple into other areas, causing growth or reduction of margins (such as plant capacities and reserve buoyancy). The management of growth and margins must be rigorous and includes hydraulic power plant loads, air conditioning loads, electronic cooling loads, electrical power loads, weight margin, ship's draft, reserve buoyancy, air system loads, and stowages. Much of growth and margin management deals with data and tracking collective trends as designs evolve.

Summary

U.S. submarines prior to the USS *Seawolf* (SSN-21) were designed without the use of sophisticated computer software and other modern tools. However, in the absence of such tools, the number of design options that can be explored is reduced. Proceeding without at least some of these tools risks design sub-optimisation and could result in a design that may not perform intended missions, may not be able to deal with better-designed foreign submarines, may become obsolete prematurely, or may have safety issues.

From the perspective of ship safety, 3D structural models are perhaps the most critical tools; they can also be used to address noise, vibration, and stress issues. Hydrostatic and pipe-stress models are also important to safety. The next most important tools, perhaps, are hydrodynamic models, without which hydrodynamic drag will be increased (reducing sprint speed by increasing power demands for given speeds and hence also reducing range). Noise created by unwanted hydrodynamic flows could also increase the detectability of the submarine and degrade the performance of its sensors at speed.

The LBES is a facility for improving the design and reliability of propulsion systems in the U.S. Navy, using full-scale replicas of engineering plants and a water tank to provide realistic loads in the propulsion system. An LBES can be used for accelerated testing during design to identify design weaknesses and increase propulsion system reliability. Hazardous evolutions, such as crash-backs, can be performed in an LBES to further test designs without risk to ship crews and while there is still time to make changes. We recommend investigation of an LBES in Australia for the Future Submarine.

APPENDIX E

Domestic Submarine Design Capability Survey

This appendix reproduces the survey used to collect information from Australian organisations within government, industry, and academia.

Person(s) Completing the Form

Name	Title/Company	Phone #	Email address

INSTRUCTIONS

Throughout this survey, please provide data by specific skill category where possible. If data are not available at the specific skill level, please provide at the Engineer/Draftsman level. In this survey "Engineers" are defined as those who perform mathematical analyses and other technical and engineering review and assessment to confirm the design products produced by Draftsmen. Engineers interpret and translate the results of research and development efforts in a manner suitable for decisions making purposes and incorporation into applicable design features. Engineers write technical specifications for submarines/ships, systems, components, tests and manufacturing processes. Engineers rarely produce finished drawings suitable for construction or construction work packages. They may produce engineering sketches to be used as guidance by Draftsmen. "Draftsmen" are defined as those who produce drawings based on engineering sketches or original work. See the notes in the table below. Additionally, please specify which skill categories are included in any "Other" or "Other Engineering" categories. Include information on all company design resources, not just those devoted to submarine design. On the next page is a table describing these skill categories.

Skill Category		Example activities/products
Draftsmen	**Those skilled in the use of design tools or developing drawings based on engineering input (typically hourly employees)**	
	Electrical	Electrical system component, electrical analysis, electrical design, power generation
	Mechanical	Mechanical component, mechanical system, mechanical design,
	Piping	Piping Design, Fluid System Design, Hydraulic System Design
	HVAC	Heating, Ventilation, and Air Conditioning Design
	Structural	Structural engineering, structural design
	Arrangements	Zone, deck, module equipment arrangements
	Other	Life Cycle Support, Software Engineering, IT Support
Engineers	**Those responsible for developing the technical characteristics and basic design (typically salaried employees)**	
	Signature Analysis	Acoustic, wake, thermal, electromagnetic and other signature analysis
	Combat Systems & Ship Control	Combat System Integration, Combat System Design, Ship Control and Navigation, Launch sequence definition, control algorithm development, Non-propulsion electronic systems, ship control systems
	Communication, sensors, intelligence systems	SONAR, sensor arrays, optical systems, communications systems, signal processing
	Electrical	Electrical generator design, distribution, load analysis, component design battery design and layout, and safety;
	Fluids	Hydraulics, chilled & cooling water; flow analysis; Computational Fluid Dynamics; flooding and casualty analysis
	Mechanical	Mechanical Component, Mechanical System, Mechanical Design, weapons handing systems; rotating machinery, auxiliary machinery, , piping system stress analysis, atmosphere control equipment
	Propulsion & Power	Shafting and Gear Design, Prime Mover Analysis, Propeller Design and Analysis, Batteries, Air-independent power generation, engine design
	HVAC	Heating, ventilation, air conditioning, induction air for engines
	Naval Architecture	Hydrostatics (weights, volumes and stability), Hydrodynamics (speed and powering analysis), ship weights, hull equilibrium;; , flooding and casualty analysis
	Planning & Production	Scheduling, manufacturing planning, production strategy development, producibility analysis; production support, zone and block outfitting planning, procurement
	Structural	Engineering analysis of all hull internal and

Skill Category	Example activities/products
	external ship structures, underwater shock analysis and modeling, foundation designs, , finite element analysis and other numerical methods used in analyzing structures
Testing	Component and system testing; test and trials plan development
Management	Programme management, planning, budgeting, large scale integration, technical management; supervision
Professional Support	Non-engineering, professional support such as technical, psychologists, computer and IT specialists
Materials	Material selection, analysis, welding, casting and non-destructive evaluation
Other Engineering	Life cycle support, cost, availability analysis, risk management, safety, environmental.

GENERAL INFORMATION

1. Briefly, what are the main components/services your company provides towards submarine design, construction, construction support, and in-service support? Please distinguish activities where you actually perform the design from those where you have oversight or approval of the design.
2. Briefly describe your overall areas of expertise in providing submarine design, construction and in service support related to: Engineering Oversight, Technical Authority, Design Authority, Engineering Products Creation, Engineering Review or Quality Assurance, Component Design, Systems Design or Manufacturing.
3. Which types of services or products related to submarine design have you provided recently? Please describe type and when.
4. Are these components and services distinct from those that you provide for other naval platforms or commercial purposes? Please describe the degree of commonality in products and services for submarine design and construction to other markets. In other words, do you sell the same product/services in all markets or is the product for submarines specialized in some way? Please describe.
5. Do you have established detailed technical specifications for your products based on national or international standards? Please list/describe those standards. If you are engaged in whole submarine or ship design efforts are these individual and other technical specifications and standards complied in a manner suitable for whole ship design and construction? Please provide a brief description.
6. How many years has your company been working in the Submarine design?
7. In submarine construction?
8. In submarine support?
9. How many years has your company existed?
10. Expected annual total revenues for 2010:
11. Annual total revenues for 2009:
12. In the next five years, do you expect your sales, revenue or business volume to: (please circle the quantity that most closely represents your expectations)
    a. Increase 25%, 50%, 75%, 100%, >100%
    b. Decrease 25%, 50%, 75%, 100%, >100%
    c. Stay the same

13. Please provide an approximate breakdown of total revenue for your lines of business:

	Percent of Total Revenue				
Category	All Lines of Business)	From New Design Work	From Alteration Work	From Construction Work	From Repair and Support Work
AUSTRALIAN Naval Sector					
Submarines					
Surface Platforms					
Other					
Foreign Naval Sector					
Commercial Sector					
Maritime					
Other					

WORKFORCE INFORMATION

14. What is the total number of full-time equivalent employees that worked for your company in 2009?
    a. How many hours per year does a full equivalent work?
    b. What percentage worked on Submarine design activities?
    c. In submarine construction activities?
    d. In submarine support activities?
    e. What percentage of employees worked on actual design drawing production?
    f. What percentage "worked in Design/Engineering oversight and approval?
15. Please provide the average number of your company's employees in 2009 and the age and experience distribution by skill category.

GENERAL DISTRIBUTION

		Average Years of Experience						
Skill Category		Number of Employees 2009	Average Age	Number over 60 years old	with Company	in Maritime Sector	in Naval Sector	in Submarine Sector
Draftsmen								
	Electrical							
	Mechanical							
	Piping/							
	HVAC							
	Structural							
	Arrangements							
	Other							
Engineers								
	Signature Analysis							
	Combat Systems & Ship Control							
	Communication, sensors, intelligence systems							
	Electrical							
	Fluids							
	Mechanical							
	Propulsion & Power							
	HVAC							
	Naval Architecture							
	Planning & Production							
	Structural							
	Testing							
	Management							
	Professional Support							
	Material							
	Other Engineering							

16. a. Please provide the average number of annual recruits and their attrition (voluntary or retirements only) by skill category over the past five years.

		2005 to 2009 Annual Average		
Skill Category		**Hired**	**Voluntary or retirements departures**	**Workforce Reductions**
Draftsmen				
	Electrical			
	Mechanical			
	Piping			
	HVAC			
	Structural			
	Arrangements			
	Other			
Engineers				
	Signature Analysis			
	Combat Systems & Ship Control			
	Communication, sensors, intelligence systems			
	Electrical			
	Fluids			
	Mechanical			
	Propulsion & Power			
	HVAC			
	Naval Architecture			
	Planning & Production			
	Structural			
	Testing			
	Management			
	Professional Support			
	Material			
	Other Engineering			

b. What is the maximum annual growth rate you could sustain as a percentage of the workforce? Does this vary by skill? If so, please provide.

c. What constrains that rate of growth (e.g. productivity, available recruitment pool, facilities, etc.)?

17. Please indicate the typical experience level of your new hires (as a percent of those hired) for both the naval and specifically with submarines.

	Naval Sector			Submarine Sector		
Skill Category	**<1 year**	**1–5 years**	**>5 years**	**<1 year**	**1–5 years**	**>5 years**
Draftsmen						
Electrical						
Mechanical						
Piping						
HVAC						
Structural						
Arrangements						
Other						
Engineers						
Signatures Analysis						
Combat Systems & Ship Control						
Communication, sensors, intelligence systems						
Electrical						
Fluids						
Mechanical						
Propulsion & Power						
HVAC						
Naval Architecture						
Planning & Production						
Structural/						
Testing						
Management						
Professional Support						
Material						
Other Engineering						

18. Where do you typically get new Draftsmen/engineers? Please describe percentages.
    a. New hires from universities?
    b. Industry?
    c. Trade schools?
    d. Transfers from other company divisions?
    e. Farm-in from engineering support companies?
    f. Farm-out of certain design details?
19. How successful have you been in hiring replacement staff in recent years? Provide detail of successful and unsuccessful recruitment pools.
20. a. Do you anticipate any future problems in hiring design staff?

    b. Are there particular worker skills that are in high demand or for which recruiting is difficult? If so, please explain.
21. Can you identify any existing untapped sources for potential recruitment? Furthermore, to what extent can the submarine design industry draw from other industries and how transferable are these skills? Provide examples.

22. Please indicate the typical number of years it takes a new, junior, inexperienced hire to become fully productive.

Skill Category		**Average years to become fully productive**
Draftsmen		
	Electrical	
	Mechanical	
	Piping	
	HVAC	
	Structural	
	Arrangements	
	Other	
Engineers		
	Signatures Analysis	
	Combat Systems & Ship Control	
	Communication, sensors, intelligence systems	
	Electrical	
	Fluids	
	Mechanical	
	Propulsion & Power	
	HVAC	
	Naval Architecture	
	Planning & Production	
	Structural	
	Testing	
	Management	
	Professional Support	
	Material	
	Other Engineering	

23. How many inexperienced people can an experienced Draftsman mentor and maintain an effective level of cost and schedule performance? If these vary by skill category, please provide details.
24. How many inexperienced people can an experienced engineer mentor and maintain an effective level of cost and schedule performance? If these vary by skill category, please provide details.
25. Please provide the average age of your workers at the time of their retirement for both Draftsmen and engineers.
26. Please list skills that are specific or unique to submarine design work in your company.
    a. Please indicate the number of personnel currently employed in those skills and the number of personnel with these skills that are needed for a new design.
    b. What submarine specialties are *not* utilized in other types of ship design programmes?

FUTURE DESIGN RESOURCE DEMANDS

27. Please provide staffing plan/demand data (headcount) for your future design efforts that is already under contract or on the books).

Skill Category		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Draftsmens											
	Electrical										
	Mechanical										
	Piping										
	HVAC										
	Structural										
	Arrangements										
	Other										
Engineers											
	Signatures Analysis										
	Combat Systems & Ship Control										
	Communication, sensors, intelligence systems										
	Electrical										
	Fluids										
	Mechanical										
	Propulsion & Power										
	HVAC										
	Naval Architecture										
	Planning & Production										
	Structural										
	Testing										
	Management										
	Professional Support										
	Material										
	Other Engineering										

UNDERSTANDING WORKLOAD

28. Which activities and skills that have the greatest impact to the schedule of a design effort. Can you please describe below the activities and the sequence that lie on the critical path for completing a design? What skill sets are associated with those activities?
29. What is the company strategy for workforce planning when demand changes? When work is ramping up, does contract funding constrain the ramp up rate? Historically, what has been the largest successful workforce ramp up rate? When work is falling off, do union restrictions or other factors affect lay-off rates?
30. What is your approach and basis for estimating new design and engineering work?
31. Describe your experience with an "Earned Value Management" system relative to cost and schedule?
32. Describe your past peak rates of design drawing production (drawings per month issued to the Shipyard shop floor)?

Design Process

33. Describe your design process (approach, organisation, etc.)?
34. How is your design process integrated with other functions (e.g. manufacturing) and the customer?
35. Please describe your configuration management process.

Design Tools and Facilities

36. What design tools do you currently use? Are the tools computer based (CAD) or traditional drafting tools? (For example Catia, AutoCAD) Are the spatial arrangement tools linked in any way to the engineering analysis tools? Does this differ by customer/market? Is your computer system part based or drawing based?
37. How many users does the system support?
38. Please describe your experience, approach and use of physical and electronic mockups as a design tool.
39. Through which stages of design (e.g. conceptual design, preliminary design, detailed design, manufacturing/production, support) do you employ these tools?
40. Have you customized these tools? If so, how?
41. What type of visualization capability do the tools used to produce spatial arrangements have? For example, can you check for accessibility and human factors issues?
42. How do these tools contain material databases, Computer Aided Manufacturing data or other data that link to your manufacturing process (if applicable)?
43. How does the system provide information that can be applied for through-life support?
44. What other computer aided analysis/simulation tools do you employ in your design work (such as finite element analysis, computational fluid dynamics, manufacturing process simulation)? Please describe.
45. a. Historically, how frequently have design systems/tools changed? What drives a change (e.g., cost, design start date, etc.)?

    b. Can you please describe the development cycle for a new design tool/system?

    c. How long does it take to install and implement such systems?

    d. How long does it take to train employees in new tools?

e. What skills are critical for successful implementation of a new design process/tool?

f. Do you have plans to upgrade or change your current design tools? If so, please describe.

46. Please describe the design related facilities you can leverage (please add additional facilities if not listed).

Facility	**On-site**	**Can access**	**Please describe**
Model walk-through/visualization			
Component/systems test facilities			
Integration testing facilities			
Conferencing facilities			
At-sea test beds			
Prototype Manufacturing			
Non-destructive test			
Computing Clusters			
Tow/Hydrodynamics test tanks; Conformation Model Testing			
Shock Testing			
Flood/Damage Testing			
Acoustic Testing			

LABOR COSTS

47. A. Please provide the average, fully burdened hourly rate (rate billed) for your employees by skill category in 2009 dollars.

Skill Category		**2009 Average**
Draftsmen		
	Electrical	
	Mechanical	
	Piping	
	HVAC	
	Structural	
	Arrangements	
	Other	
Engineers		
	Signatures Analysis	
	Combat Systems & Ship Control	
	Electrical	
	Fluids	
	Mechanical	
	Propulsion & Power	
	HVAC	
	Naval Architecture	
	Planning & Production	
	Structural/	
	Testing	
	Management	
	Professional Support	
	Material	
	Other Engineering	

B. What are your standard work hours per year?

48. A. Please provide your annual training cost (any cost beyond trainee salary) per worker for Draftsmen and engineers.

B. Are there any skills that have significantly higher training costs? Please describe.

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